ANALYSIS OF COMPETITION AND PHOSPHORUS RESPONSE IN MAIZE/SOYBEAN AND MAIZE/RICE INTERCROPS IN RELATION TO SOIL PHOSPHORUS AVAILABILITY IN DIFFERENT ENVIRONMENTS

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ABSTRACT

While the effect of nitrogen on intercrops has been extensively studied, little information is available on P effects. There is a dearth of information on how intercrops respond to varying levels of soil P availability leading to more efficiency. Field experiments were therefore conducted at University of Hawaii Experiment Stations in three environments to evaluate the productivity of intercrops, leaf properties, and root dry matter in relation to P in the soil solution. Intercrops of maize with soybean or rice were established at ten levels of soil solution P and evaluated against sole crop checks for grain yield, dry matter production, P uptake and P use efficiency to determine whether the increased productivity of the mixture was only due to increased uptake of resources or efficient conversion to dry matter or grain yield by intercrop components under competition.

Differences between environments were large relative to the effects of P and intercropping systems. The response of grain and total dry matter yield to P ($\partial Y/\partial P$) was proportional to the inverse of P level for both maize and soybean in each environments. The response of the intercrop maize to P, was similar to that of the sole crop. The presence of soybean with maize had little effect on the performance of intercrop maize, however soybean yields were significantly reduced. The response of intercrop soybean to

environment and P level was different than its sole crop. Grain and dry matter yield of sole crop soybean increased with increased P availability whereas intercrop soybean yield decreased. The magnitude of the increase or decrease (slope) depended on environment and the sign of the slope changed by intercropping. Higher maize yields across environments and P levels were associated with reduced growth of intercrop soybean.

Intercrop advantage, as measured by the Land Equivalent Ratio, and the competitiveness of soybean decreased as P availability increased. The increased competitiveness of intercrop maize at high P levels was correlated with a reduction in yield of intercrop soybean. The advantage due to intercropping was maximum under low soil P availability under a wide range of environmental conditions.

Growth of intercrop maize was no different than the sole crop for their leaf properties and P uptake, but was profoundly affected by environment and P availability in the soil. Soybean leaf properties, leaf tissue P concentration and P uptake were affected by environment, P level and intercrop system and their interactions. Phosphorus uptake increased as the availability increased irrespective of the environment and cropping system.

Phosphorus use efficiency, measured as the grain yield or dry matter per unit of P uptake, decreased with increased P availability. Taken together, the intercrops extracted more P than sole crop maize. P use efficiency was reduced by intercropping.

Total root biomass (dry weight) in the surface layer of the intercrops was higher than in the sole crops, with the difference changing according to P levels and year. An estimate of LER based on root dry weight was within the range calculated using above-ground dry matter or grain yield.

The increased productivity of intercrops was associated with increased P uptake. In low-input subsistence agriculture, accelerated P mining -- the faster removal of limited soil P -- may cause the intercrop systems to be less sustainable.

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1.

INTRODUCTION

Intercropping is the growing of two or more crops simultaneously on the same field during a growing season. Crop intensification is both in time and space dimensions (Andrews and Kassam 1976). Such an intensification usually gives higher overall yields compared to sole cropping, though intense competition may result in lower yields of some components. Intercrop components influence each other by changing their environment (Harper 1977). The actual mechanism of change determines the end results. Many growth factors are influenced by a number of management variables that affect the outcome and predictability of intercropping. In ecological terms, the morphological and physiological differences among species result in their ability to occupy different niches. Observed differences include the timing of resource interception, location of resource interception, rate of resource absorption, rate of growth and response of yield to the levels of resources availability (Trenbath 1986).

In this context, how the intercrop components differ in response and extraction of nutrient resources compared to the sole crop situation, under different productivity and environmental conditions, is pertinent in quantifying the effect of competition and evaluating its contribution towards an intercrop yield advantage.

The research in this thesis aims to test the following hypotheses:

A. The relative advantage of intercropping over sole cropping increases with decreases in soil productivity.

B. Complementary effects in intercrops of diverse rooting component crops are significant due to positive below ground interactions.

Intercropping with maize (*Zea mays* L.) as a main crop is a common practice in large areas of the tropics and subtropics where subsistence agriculture is the way of life. The companion crops include a wide range of crops varying in growth characteristics and rooting patterns, such as legumes, root crops, and other cereals. Soybean (*Glycine max* L. Merr.) is a relatively new crop in areas of the tropics but holds great promise as a rich protein source.

The additional input of chemical fertilizer is nonexistent or negligible in developing countries. Intercropping may have the potential to increase food and protein production without the use of costly inputs. To increase food production in these deficit areas, research must be directed towards nonmonetary inputs and increasing the efficiency of the meager resources available to farmers.

For years, agricultural scientists were skeptical about the benefit of intercropping which was rejected as a primitive practice that would give way to sole cropping as a natural and inevitable consequence of agricultural development (Willey 1979). Fortunately, in recent years there has been great interest and awareness in the rationale of intercropping. Farmer's wisdom of deriving benefit simply by mixing two crops and not by costly inputs is recognized. Popular intercropping systems were evolved through experience and repeated trial and error over generations. It is likely to continue in the future. Improvement in these systems is possible through understanding how the growth of component crops respond to different environmental factors. The success of any intercrop combination in terms of its advantage over the component sole crops lies in understanding the intricate and complex interactions of these factors and their separate effects.

Most of the research in the past has emphasized cereal/legume intercropping systems and nitrogen economy. Many studies on intercrops have used varying levels of nitrogen to evaluate intercrop productivity and advantage (Searle et al 1981, Francis and Stern 1986,1987, Ezumah et al 1987, Kausik and Gautam 1987). Research on the role of other nutrients in intercropping has been sparse and very little research has been done on competition for phosphorus. Because phosphorus is highly immobile leading to a small zone of depletion around roots, the response of intercrops to fertilizer phosphorus may not be similar to nitrogen. My objective in this thesis is to assess the effect of competition, uptake and efficiency of phosphorus as well as the productivity of maize/rice (*Oryza sativa* L.) and maize/soybean row intercrops with varying P availability under different environments.

The overall objectives were:

1. To evaluate the growth, productivity, and phosphorus response of maize/rice and maize/soybean intercrops.

2. To analyze competition, uptake, and phosphorus use efficiency in sole and intercrops in relation to P availability.

3. To study plant root growth and interaction in intercrops in relation to P availability.

2.

REVIEW OF LITERATURE

2.1 RATIONALE FOR YIELD ADVANTAGE

Extensive reviews by many authors have suggested that the advantage in intercropping is typically due to (a) better utilization of available resources (Andrews and Kassam 1976, Willey 1979), (b) better control of weeds because of a more competitive plant community in space or time than sole cropping (Litsinger and Moody 1975, Rao and Shetty 1977) and (c) better control of diseases and pests as a result of diversity (Baker and Norman 1975, Finlay 1974, Raheja 1977).

Willey (1979) outlined three circumstances where intercropping will have advantages over sole cropping.

A. When intercropping gives a full yield of a main crop and some yield of a second crop.

B. When the combined yield of intercrops must exceed the higher sole crop yield.

C. When a combined intercrop yield exceeds combined sole crop yield.

Agronomic advantages of intercropping occur when there are complementary interactions due to spatial and temporal difference in resource use such that interspecific competition is less than intraspecific competition (Willey and Reddy 1981). Complementary effects are not well understood partly because most of the research performed with replacement series intercrops (research on additive mixture are few), though helpful for evaluating the gross effect of competition and compensation, do not shed much light on the internal interactions in the system that lead to final yield (Francis 1989). Connolly (1986) claimed that the fundamental difficulty with the replacement series method stems from ignoring the two-dimensional nature of mixture, the density of each mixture being independently variable. A replacement series consists of points on a one-dimensional line in this two-dimensional mixed-density plane. The concept of overall density as used in replacement series methods is usually meaningless; the separate identities of species are submerged in a purely formal numerical equivalence (Connolly 1988). He concluded that replacement series is usually a misleading tool for research on mixtures. Replacement series do not represent farmer's intercrop field conditions and seem to be artificial.

2.1.1 Resource use

Most of the interpretation of the intercrop advantage has dealt with the efficient use of resources by intercrops. To understand the mechanisms that result in this advantage, Trenbath (1986) proposed resource use efficiency, RUE, as:

RUE = Capture efficiency * Conversion efficiency

$$= ((R_i/R_0) * (R_a/R_i)) * ((B/R_a)*H)$$ where

R_0, R_i, R_a are quantities of resources potentially available, intercepted and absorbed, respectively, per unit area integrated over the growing season. B is the whole plant biomass and H is harvest index. The concept was extended to establish the completely additive model of Land Equivalent Ratio (LER, defined below). LER, which is the measure of advantage, has been shown by Trenbath to be composed of additive contributions of unity, deviation from unity due to absorption, deviation due to differences between conversion efficiencies in sole crop and intercrop, and deviations due to interactions between absorption relationships and the differences in conversion efficiency. This concept is equally applicable to any resource such as light, nutrient and water.

2.1.2 Yield stability

The main cause of the predominance of intercropping systems in poorly developed agriculture is its greater stability over different seasons. The logic usually cited is that if one crop fails the other can utilize more resources by itself. Studies on the stability aspects of intercropping have indicated more positive effects rather than lack of it, especially under resource limiting condition (Rao and Willey 1980).

2.1.3 Diversity

It has been hypothesized that stability is closely related to diversity. Intercropping, being a more diverse system than sole cropping, poses restrictions on the abundance of insect herbivores, disease and their spread. Examples of specific crop mixtures that result in reduced pest incidence are common (Pimental 1961, Trenbath 1974, Matteson et al 1984). The explanations for such behavior, summarized by Altieri (1986), are (i) the natural enemy hypothesis and (ii) the resource concentration hypothesis.

There is a greater abundance of natural predators in diverse systems such as intercrops, presumably because of greater availability of habitat and resources compared to a sole crop situation. Thus, pest populations are under control. The resource concentration hypothesis is the same as the fly-paper effect of Trenbath (1976) and disruptive crop hypothesis of Vandermeer (1989). Herbivore populations are influenced by spatial dispersion of food plants. Either the herbivore is less likely to find a host plant because of some kind of confusion (physical or chemical) or the food source becomes less apparent by the presence of a second species. The spread of pathogenic spores is hindered by a diversity of plant species. Environmental modification in intercrops can delay onset of disease.

2.1.4 Ecological niche

The yield advantage, especially in traditional intercropping systems, occurs because of efficient absorption of resources resulting from differences in niches and distribution of growth factors in space and time. The idea stems from fundamental ecological axioms that two species can not occupy the same niche; if they do, one will ultimately be excluded. However, the overlapping of fundamental niches of intercrop components may exert an effect on the environment and also respond to the environment thus affected. The overall interaction determines the intensity of competition.

2.2 COMPETITION AND PLANT INTERACTION

Clements (1929) stated "when the immediate supply of a single factor falls below the combined demands of plants, competition begins". This competition may be among plants of the same or different species. Competition is only one aspect of plant interactions. When two crops are grown as intercrops, plant interaction may result in mutual inhibition, cooperation and compensation. To establish the presence of plant interaction, one standard is to compare the growth of intercrop components with their growth in the sole crops. The type of plant interaction is highly dependent on the ratio of the densities of intercrop components and the population density of each. In the early stages of plant growth, competition is usually between the same species (i.e. in alternating row intercrops. A new dimension (interspecific competition) is added when a crop of another species also exerts pressure for its share of resources. Later, plant growth may be suboptimal as a result of competition which depends on the level of resource availability and population densities of the intercrop components. The physical aspects of intra- and interspecific competition are the same; it does not matter to a plant whether its roots are competing for resources with the roots of other plants of the same species or another species. Differences in plant distribution and shoot and root geometry of component crops make spatial relationships and intensities of competition different (Trenbath 1976). This principle applies to other growth resources such as sunlight, water, and nutrients. Complementary crop mixtures based on different resource needs (either physiological or temporal) permit crop mixtures to overyield. The most commonly invoked explanation for yield reductions in intercropped mixtures is the removal reaction through competition for limited resource (Gliessman 1986).

Many classifications of plant interactions have been presented but the most comprehensive one is that of Odum (1971), which includes plant/animal and animal/animal interactions and the resulting effects on the population of each species.

The classification presented by Hart (1974) describes the mechanism of interaction that results in favorable or unfavorable effects on each of the component species grown together. The interaction is (a) commensalistic, when there is positive effect on one species and no effect on the other, (b) amensalistic, when there is a negative effect on one species and no effect on the other, (c) monopolistic, when the interaction has a positive effect on one species and a negative effect on the other, (d) inhibitory, when the interaction effect has a negative effect on both the species.

It is difficult to determine the contribution of each factor such as light interception, conversion efficiency, efficient nutrient and water uptake to yield advantage in an intercrop. Efficiency and uptake are affected due to different periods of rapid growth and peak requirements of the component crops. Research on this problem must focus on partitioning the resources used by intercrop components, and the interaction of shoots and roots. Willey and Reddy (1981) described a technique for separating above and below ground interactions in intercropping in their studies on pearl millet/groundnut intercropping using vertical polythene partitions. They observed that above ground interactions were significant and the main determinant of yield advantage. However the below ground interaction was important in determining the competitive balance of the two component crops. The same technique can be use in quantifying below ground interactions by putting a polythene partitions above ground in row intercrop systems.

2.3 MEASURE OF COMPETITION AND INTERCROP ADVANTAGE

2.3.1 Land Equivalent Ratio

LER has been used extensively to evaluate the advantage in productivity of intercrop combinations in relation to comparable sole crops. LER in numerical terms is defined as the sum of the fractions of intercrop yield to that of the sole crop under similar environmental condition. In other words, for the case of a two species (a and b), LER is the sum of two Partial Land Equivalent Ratios (PLER):

$$\begin{aligned} LER &= PLER_a + PLER_b \\ &= \text{intercrop yield}_a/\text{sole crop yield}_a \\ &+ \text{intercrop yield}_b/\text{sole crop yield}_b \\ &= Y_{ab}/Y_{aa} + Y_{ba}/Y_{bb} \quad \text{where} \end{aligned}$$

Y_{ab} = intercrop yield of species_a, Y_{aa} = sole crop yield of species_a, Y_{ba} = intercrop yield of species_b, and Y_{bb} = sole crop yield_b.

The LER value can either be

> 1 (intercropping advantageous)

= 1 (no net effect of intercropping)

< 1 (intercropping disadvantageous)

In conceptual terms, LER signifies the amount of land area under sole crops required to equal the yields produced by the intercrop combination. Because density is very important in LER estimation, Trenbath (1976) suggests that comparable sole crops be at optimum density to quantify LER and hence the advantage in intercrops.

2.3.2 Relative Crowding Coefficient (K_{ab}) of component a

The relative crowding coefficient was proposed by de Wit (1960). The coefficient denotes whether the components have produced more than expected or not.

Relative crowding coefficient (K_{ab})

= (mixture yield$_a$ * proportion of b with a) /

(pure stand yield$_a$ - mixture yield$_a$)* proportion of a with b

or symbolically

$$K_{ab} = Y_{ab}*Z_{ba} / (Y_{aa} - Y_{ab})*Z_{ab}$$ where

Z_{ba} is the proportion of b with a, and Z_{ab} is the proportion of a with b. The value of K_{ab} can either be

> 1 (intercrop component a produced more than expected)

= 1 (intercrop component a produced equal to expected) and

< 1 (intercrop component a produced less than expected).

2.3.3 Agressivity

This index, proposed by McGilchrist (1965), denotes which intercrop component is dominant and more competitive over the other.

Symbolically, agressivity

$$A_{ab} = (Y_{ab}/Y_{aa})*Z_{ab} - (Y_{ba}/Y_{bb})*Z_{ba}$$ where

A_{ab} (agressivity of a on b) = 0 signifies that components are equally aggressive and competitive. The positive value components will be aggressive and dominant over the negative value components.

2.3.4 Competitive ratio (CR)

This index, proposed by Willey and Rao in 1980, is the ratio of two partial LER's adjusted for their proportions in the mixture.

$CR_a = ((Y_{ab}/Y_{aa})/(Y_{ba}/Y_{bb}))*Z_{ba}/Z_{ab}$ where

CR_a is the competitive ratio a.

The index determines the competitiveness of one species over the other. It has been proposed for evaluating the competitive balance between components and the change in competitive balance in intercrop combinations subject to treatment effects.

2.4 QUANTIFICATION OF INTRA- AND INTERSPECIFIC COMPETITION

A number of terms and models have been developed to describe inter- and intraspecific competition (Hart 1974, Trenbath 1974). Willey (1979) on the basis expected yield (i.e. when intra- and interspecific competition was equal) classified cases of deviation from expected yield in mixtures as (a) mutual inhibition (seldom occurs) (b) mutual cooperation, and (c) compensation (most common situation). Compensation results involve mixtures of competitive (dominant) and less competitive species. Willey (1979) used examples of replacement series, which compare a series of density combinations ranging from a pure stand of species A through various mixtures to a pure stand of species B, to illustrate the theoretical concepts.

The conceptual models help to describe the gross effects of competition and compensation, but do not shed any light on the internal interactions in the system that lead to final yields (Francis 1989). The fundamental difficulty is that a replacement series is one dimensional, being points on a single line in the two dimensional density plane. The two dimensional density effects are being distorted or confounded on reduction to one dimension (Connolly 1986). The arbitrary reference, pure stands used to calculate relative performance of an individual in a mixture will have an influential effect.

In recent years multivariate response models have been used to estimate intra- and interspecific competition (Spitters 1983, Firbank and Watkinson 1985, Connolly 1988) in intercrops and crop weed mixtures. So long as there is no interference by neighboring plants of the same or other species the density-yield relationship is linear. This is possible at very low density in mixtures and in sole crops. At higher densities the response is restricted by competition for resources. In mixtures, the density response is different from a pure stand. It is necessary to grow both a pure stand and a mixture over a range of densities to separate the effects of intraspecific and interspecific competition (Firbank and Watkinson 1985).

Spitters (1983) described the intraspecific competition (density response) in monoculture by the equation of a hyperbola:

$$\mathbf{Y = N/(b_0 + b_1N)}$$

where Y is yield (g m^{-2}) and N is density (plants m^{-2}). With w being g $plant^{-1}$, the equation can be written in inverse form as:

$$\mathbf{1/w = b_0 + b_1N}$$

The intercept (b_0) of this equation represents the reciprocal of virtual biomass of an isolated plant and the slope (b_1) represents the decrease in per plant weight with increase in density. The slope b_1 is the reciprocal of the maximum biomass per unit area at infinite density. At very wide spacings there is no interplant competition so per plant weight remains constant with decreasing density and does not increase as is suggested by the hyperbolic equation.

Spitters (1983) found that the inverse weight of a plant in a mixture is a function of the density of each component.

$$\mathbf{1/w_1 = b_{10} + b_{11}N_1 + b_{12}N_2}$$

$$\mathbf{1/w_2 = b_{20} + b_{21}N_1 + b_{22}N_2}$$ where

the coefficient b_{11} measures the intraspecific competition effect for the first species and b_{12} quantifies the effect of interspecific competition of species 2 on species 1. This approach can deal with additive mixtures where the population is more than the pure stand. The original de Wit model holds only when Relative Yield Total (RYT) = 1, that is when there is no niche differentiation (see appendix 1 and 2 of Spitters 1983 for details). Relative yield total is calculated with the same equation as LER, but RYT is restricted to replacement series examples (LER is normally based on agronomically meaningful densities for sole crops and intercrops).

Since growing pure stands and mixtures over a range of densities are required to separate the effects of intraspecific and interspecific competition, the response model may not be feasible where intercrops are evaluated for large numbers of other factors. In this thesis the response model approach (using a regression model incorporating the densities of intercrop components) was not followed because of large numbers of factors other than population density.

2.5 SOIL PHOSPHORUS, SUPPLY AND UPTAKE BY PLANTS

The phosphorus present in the soil can be divided into four groups: (A) phosphorus as ions and compounds in the soil solution, (B) adsorbed phosphorus on the surface of inorganic soil constituents, (C) phosphorus in mineral form and (D) phosphorus as a component of soil organic matter (Barber 1984). All the forms of phosphorus are in dynamic equilibrium and are never static. The availability of phosphorus to growing plants depends on soil characteristics that control the supply of P, as well as plant characteristics which regulate its uptake. Besides fertilizer application, crop removal and root characteristics play an important role in P uptake.

The uptake of nutrients by crops depends on the capacity of the soil to maintain a constant supply to the roots as well as plant factors such as root absorbing power and geometry. The interaction of these factors is also important. The supply depends upon the P in soil solution (intensity factor) and the ability of the soil to supply P to the solution from the solid phase (capacity factor) (Khasawneh and Copeland 1973). Since P supply to roots and uptake by plants are dynamic processes, the flux through the soil and root system determines the ultimate uptake. The nutrient uptake models of Classen and Barber (1976) and Barber and Cushman (1981) integrate detailed information and knowledge of these processes. A brief review is presented to (a) evaluate how soil and root characteristics influence the parameters used in the model which in turn affect the prediction of phosphorus uptake and to (b) examine whether the predictions will be valid in a mixed cropping situation, and if not how the parameters may be affected.

2.5.1 The model parameters

Mechanistic models (Claassen and Barber 1976, Barber and Cushman 1981) that describe the movement of nutrients in the soil towards plant roots by diffusion and mass flow have been used to study nutrient uptake by plants growing in soil (Schenk and Barber 1980, Silberbush and Barber 1983, 1984, Kovar and Barber 1988).

The Barber Cushman model uses 11 soil and plant parameters (see Barber 1984 for definition of parameters) to calculate diffusion and mass flow of nutrients to root surfaces and uptake of nutrients from soil solution by growing plant root systems. The parameters C_{li}, D_e, and b determine the soil nutrient supply. The parameters L_0, k, and r_0 give the amount of absorbing surface, geometry, and rate of change respectively. Root density, morphology, and physiology are important for resultant uptake if the nutrient flux is not restricted by a supply parameter. Root morphology may be defined by the root radius, root length, root surface/shoot weight ratio, and root hair density. The flux of nutrients through the root is dictated by its physiology, the kinetics of which are characterized by maximum rate of net influx (I_{max}), the Michaelis-Menten constant (K_m) and minimum concentration (C_{min}) in solution below which net influx does not occur.

2.5.2 Effect of root characteristics

Schenk and Barber (1979, 1980) studied root characteristics of maize genotypes as related to phosphorus uptake in solution culture, pots, and field experiments. They observed that plant utilization of P applied to soil is usually low and may be increased by having more roots present or by improving P uptake characteristics of the roots. Shoot yield of all the maize genotypes increased by increasing P levels, which had little effect on the amount of roots. The prediction of P uptake was very close to observed P uptake only at high P levels and not at low soil P levels. Similar result has been obtained with soybean cultivars by Silberbush and Barber (1984). Additional factors such as root hairs, mycorrhizae and root exudates were supposedly involved at low P levels. At higher P levels the model predicted the P uptake accurately because root surfaces were the main sink due to few root hairs and a larger diffusion coefficient (D_e). Significant differences between genotypes in physiological and morphological characteristics of roots influenced the P uptake by maize plants. The model parameters varied considerably between genotypes, especially I_{max} and C_{min}. Both were positively correlated with K_m which indicated that genotypes either had an advantage at high P supply or were superior at very low P levels, but did not combine both properties. In pot experiments they found strong positive correlations between root surface and observed P uptake. Soil type influenced the root morphology especially the root diameter. Mean distance between roots increased as amount and length of roots decreased. In field experiments significant differences in root morphological and physiological parameters resulted in marked differences in P uptake.

Distribution of roots between top soil and subsoil as well as root surface per unit of shoot varied among genotypes and soils.

2.5.3 Effect of soil characteristics

Schenk and Barber (1979) equilibrated six different soils at 70°C for six days followed by one week at 25°C so P levels would change only due to uptake during the experiment. They measured soil as well as root parameters to predict the uptake of phosphorus. The prediction was close to 1:1 with observed value. The slope of the regression line and correlation were close to unity.

Kovar and Barber (1988) investigated the P supply to plant roots as affected by phosphorus addition and supply characteristics of 33 different soils. They determined the values of soil solution P (P_L) and adsorbed P (P_S) for seven rates of applied P, ranging from 0 to 655 mg P Kg^{-1} on 33 soils. A curvilinear relationship of the form $P_L = ax^c + d$ describes the relationship of P addition (x) to that of P_L. The curvilinearity constant c ranged from 1.03 to 3.15, and the value of the coefficient a, which determines the linear increase in P with P addition, was small because only a fraction of P ends up in the soil solution. The value of d (y-intercept) which is the intrinsic soil P, ranged from 0.036 to 0.55 mg L^{-1}. A first order linear polynomial, $P_S = hx + g$ best described the relationship between added P (x) and P_S (r^2 = 0.91 to 1). The slope (h = proportion of added

P extracted) values were positively correlated with the diffusion coefficient (D_e), and the Freundlich equation, $P_S = m (P_L)^n$, where m and n are regression constants, represented the relation between P_S and P_L. Soil type had a profound effect on P supply to plant roots since P supply is influenced by both P_S and P_L through its effects on buffer power (b) and D_e.

2.5.4 Model prediction

Even though it is difficult to consider the assumptions in the Barber Cushman model valid in field conditions, the validation of the model seems to be satisfactory, at least for optimum growth conditions. Uptake predictions were not satisfactory at low levels of P in soil solution, mainly because of effects on root surface per unit of shoot which were highest in soils having the lowest soil solution P. This may be due to the relatively higher volume of soil being explored by roots at low phosphorus availability. Maize roots grown at low P supply have been shown to have an increased root surface to shoot weight ratio (Schenk and Barber 1979). Root exudates, mycorrhizae, and root hairs have a significant effect on uptake at low P supply and have been implicated as causing the underprediction of P uptake by the model.

2.5.5 The intercropping scenario

Phosphorus is highly immobile in soil. Diffusion is the dominant process by which phosphorus reaches the root surface (Nye 1966). Diffusion is initiated by the concentration gradient due to depletion at the root surface and the plant root itself is affected eventually (Nye 1966, Nye and Tinker 1977). Kraus et al (1987) studied the dynamics of development and replenishment of P depletion zones around the roots of maize under low P availability. Because growing roots depleted the solution phosphate more quickly than replenishment could take place, depletion zones developed around the roots. The extent of the depletion was defined as the distance from the root surface to where the P concentration profile approached about 95% of the P concentration of the undisturbed soil. This distance will have implications in mixed cropping situations. The depletion zone extends up to a maximum of 0.86 mm wide, then begins to shrink. Assuming that the same assumptions are valid in intercropping situations, the model may not be adequate to account for expected increased depletion of P due to intermingling roots of different species.

The original model developed by Claassen and Barber (1976) did not consider competition between roots for nutrient absorption. The Barber Cushman model incorporated competition by taking into account the half distance between neighboring roots. It is unclear whether this is enough to quantify competition between roots of two species as well as between the same species.

When two species are grown together the distribution of roots in the soil profile and their relative aggressiveness become the primary determinant in the competition and uptake of phosphorus by component species. A cereal component is more competitive and aggressive than a legume component due to the cereal's more extensive root system. The uptake model assumes uniform root distribution in the soil profile. In intercropping situations, roots tend to be distributed according to niche preference. Further, component species of different rooting pattern tap different soil volumes. This, of course, depends on species, row arrangement, ratio, and density of components. All these factors influence the relative competitive ability of component species in extracting nutrients from the soil medium. Experimental evidence on how the parameters in the model will change with species, row arrangement, component ratio and density is not presently available.

Except for r_1 (half distance between roots), which considers competition between roots by assuming radial nutrient movement to a limited distance, most of the parameters in the Barber Cushman model may be expected to be the same in intercropping. Strong competition for nutrients between roots of different species has been documented (Wahua 1983) as well as among roots of the same species. Fusseder et al (1987) observed no competition between roots of adjacently grown plants in either pure or mixed stands.

However, the P depletion cylinders on approximately one third of the roots of an individual maize plant were found to overlap. Fusseder's calculation of r_1 is based on root density of the sole crop, which can be expected to vary significantly in intercropping.

The accuracy of the Barber Cushman model is questionable in the field, especially in low fertility conditions. The model may be very useful in understanding different soil processes governing nutrient uptake by crops. Interspecific competition needs to be taken into account for predicting nutrient uptake by intercrop components.

2.6 PHOSPHORUS UPTAKE BY INTERCROPS

From the small amount of literature available on the subject it is suggested that the total uptake by intercrop components is more than that of sole crops (Dalal 1974, Agboola and Fayemi 1971, Wahua 1983). Kausik and Gautam (1987) studied nitrogen and phosphorus effects on pearl millet/cowpea or green gram intercropped under rainfed conditions and reported increased productivity of the intercrops. The intercrops were more responsive to N at lower nitrogen levels. While there was no response of phosphorus in sole crops of pearl millet, there was a significant response in intercrops. However, this experiment was not designed to separate interactions from main effects.

In replacement series experiments, the population densities of a particular species in the intercrop and sole crop are not the same, by design. The uptake of nutrients by the sole crop has been compared to overall total uptake by the mixture. The increased uptake of a nutrient by a mixture may result from the tapping of nutrients at different locations and sources as well as by one species mining a source not available to the first (Vandermeer 1989). In additive mixtures where the population of one component is the same as in the sole crop, how P uptake and efficiency are affected under extremes of deficiency and availability needs to be investigated.

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3.

ENVIRONMENTAL EFFECT ON PRODUCTIVITY OF MAIZE/RICE AND MAIZE/SOYBEAN INTERCROPS IN RELATION TO SOIL PHOSPHORUS

3.1 SUMMARY

While the effect of nitrogen on intercrops has been extensively studied, little information is available on phosphorus effects. Field experiments were therefore conducted at University of Hawaii Experiment Stations to evaluate the productivity of intercrops and to quantify the environmental effects in relation to phosphorus in the soil solution. Intercrops of maize with soybean or rice, and their sole crops, were established at ten levels of soil solution P in three environments and evaluated for phosphorus response, total dry matter and grain yield.

Differences between environments were large relative to the effects of phosphorus and intercropping systems. The phosphorus responses, $\partial Y/\partial P$, of sole and intercrop maize were similar across environments whereas soybean yield increased with P level in the sole crop but decreased with P level in the intercrop. The response of grain and total dry matter yield for both maize and soybean in each environment and system was proportional to the inverse of phosphorus levels.

The intercrop advantage as measured by the Land Equivalent Ratio and the competitiveness of soybean decreased as phosphorus availability increased.

The increased competitiveness of intercrop maize at high phosphorus levels corresponded to the reduction in yield of intercrop soybean. Intercropped maize yields were only slightly reduced relative to the sole crops. The presence of soybean had little effect on the performance of intercrop maize, however intercropped soybean yields were significantly reduced.

The advantage in efficiency due to intercropping was maximum under low soil phosphorus availability under a wide range of environmental conditions.

3.2 INTRODUCTION

Published research has indicated advantages of intercropping systems over sole cropping under various conditions of plant growth (Allen and Obura 1983, Harris et al 1987). The advantage of intercropping has been attributed to the improved use of resources, particularly light, water, and nutrients (Willey 1979, Marshall and Willey 1983) and the complementary effects due to spatial and temporal differences in resource use. It has been hypothesized that the improved resource utilization was due to niche separation (Trenbath 1986), increased root density and proliferation of roots in intercropping which results in a greater volume of soil being explored.

The efficiency of cereal/legume intercrops, in terms of the Land Equivalent Ratio (LER), has been shown to remain unchanged or decrease in response to increasing nitrogen levels (Ahmed and Rao 1982, Searle et al 1981, Baker and Blamey 1985, Ofori and Stern 1986). Experiments with phosphorus are sparse (Remison 1978, Chang and Shibles 1985) and none were found with rice as an intercrop component. The effects of soil solution P on intercrop performance and the interaction of the P effect with the environment have not been investigated. This section of the thesis deals with the effect of the environment, soil phosphorus, and intercropping on yield and yield components of maize and soybean in maize/rice and maize/soybean intercrop systems.

Because the nutrient response may be different for intercrops and may change with environments, the outcome is unpredictable. It is unclear how these relationships are affected by different environmental conditions, in spite of numerous experiments with different nitrogen levels in intercrops. Therefore, information on the extent of competition and phosphorus response in intercrops would help in evaluating management options and design of intercropping systems.

The external phosphorus requirement (EPR), defined as the predicted concentration of soil solution P at which 95% of the maximum attainable yield was realized, is not a single value that holds for all conditions (Fox 1981). The concept was developed for sole crops; no literature was found that measured EPR for intercrop components.

In order to predict the overall performance of any intercrop combination it is essential to understand the nature of differences in the P response of intercrop components and their interactions with the environment. I hypothesize that the shape of the response surface is largely influenced by the environment and its interaction with soil P availability and also by the competitiveness of intercrop components. At times, the interaction may be more important than the main effect of P and differences due to intercropping. Only by understanding these complex interactions can recommendations and extrapolations to other locations have any validity.

The objectives of this research were to

i. **evaluate the yields of intercrop components,**

ii. **quantify intercrop advantage in productivity, and**

iii. **quantify the competitiveness of intercrop components** in relation to soil P availability in different environments.

3.3 MATERIALS AND METHODS

3.3.1 Location of experiment, site and soil description

Two sites in Hawaii, having contrasting soil and climatic conditions, were utilized to conduct an experiment in three environments (Table 1). Climatic data during the growth period of the crops in the experiments are in Appendix 14.

Table 1. Climatic parameters for experiment station experimental sites where field trials were conducted.

Sites	Latitude North	Longitude West	Elevation m	Temp. (°C) Max	Min	Rainfall mm/year
Kauai	22 04'30"	159 24'45"	162	25.55	20.00	2489
Poamoho	21 32'30"	158 05'15"	190	27.22	19.44	1118

Permanent plots, where ten target phosphorus concentration in soil solution have been maintained since 1971, were utilized for the intercropping experiments. The field trial at Wailua Experiment Station, Kauai, was planted in 1987 on a highly weathered clayey, sesquic, isothermic, Anionic Acrudox. Two field trials were conducted during the summers of 1988 and 1989 at the University of Hawaii Poamoho Experiment Station on a silty clay of the Wahiawa series classified as clayey, kaolinitic, isohyperthermic, Rhodic Eutrustox.

3.3.2 Treatments and experimental design

Main plots of ten target P levels (0.003, 0.006, 0.012, 0.025, 0.05, 0.1, 0.2, 0.4, 0.8, and 1.6 mg P/L in soil solution) were laid out in an augmented block design (Federer 1956). The target P levels in soil solution were achieved using phosphorus sorption techniques (Fox and Kamprath 1970). Appropriate amounts of P fertilizer in each treatment were applied as triple super phosphate before the last tillage operation to achieve the targeted levels of P in soil solution (Appendix 10.2). In Kauai, the four middle P levels (0.025, 0.05, 0.1, and 0.2 mg P/L) were replicated three times, the four extreme levels (0.003, 0.006, 0.8, and 1.6 mg P/L) were not replicated and the remaining two (0.012 and 0.4 mg P/L) were replicated twice. Each of 20 main plots (12.19 by 9.14 m^2) contained each of the three sole crops (maize, rice, and soybean) along with maize/rice and maize/soybean intercrops. The treatments and experimental design at Poamoho were slightly different from Kauai. Four P levels, 0.012, 0.025, 0.050 and 0.100 mg P/L were replicated three times and the rest of the unreplicated treatments constituted the 18 main plots (15.24 by 5.49 m^2). Each main plot contained one of the sole crop (maize, rice or soybean) and the two intercrop patterns in 1988. In 1989, main plots contained the maize/soybean intercrop with both maize and soybean sole crops (Table 2).

Table 2. Date of planting and subplot treatment allocation within main plots across environments.

	Kauai (1987)	Poamoho (1988)	Poamoho (1989)
Phosphorus plots	20	18	18
Sole crops	M, R (20)	M, S, R (6)	M, S (18)
Intercrops	MR (20)	MS, MR (18)	MS (18)
Date of planting	Nov.17	May 17	June 8

Maize:M, Soybean:S, Rice:R, Maize/Soybean:MS Maize/Rice:MR, Numbers in parenthesis indicate number of plots allocated for each system in each field trial.

3.3.3 Planting and harvesting

Maize spacing was 0.90 m by 0.25 m for both sole crop and intercrop. Sole crop rice was planted in a row spacing 0.30 m at a seeding rate of 100 kg/ha. Two rows of rice were planted between two rows of maize in the maize/rice intercrop. Sole crop soybean was spaced at 0.45 m by 0.10 m. Intercrop soybean was spaced at 0.90 m by 0.10 m apart as alternate rows with maize so that it had half the population of sole crop soybean. In 1989, because of bird damage to the seedlings, soybean was replanted 4 days after the emergence of maize. Nitrogen from urea and potassium from potassium chloride were supplied at a rate of 150 kg/ha for each crop before planting. Soybean was inoculated with rhizobium. A drip irrigation system supplied the water at Poamoho but the Kauai experiment was rainfed. Experimental plots were maintained weed free by two hand weedings (30 and 75 days after planting) in 1988. In 1989 weed control was accomplished with a preemergence application of alachlor (Lasso) herbicide followed by a post emergence spray of bentazon (Basagran). There was a slight phytotoxic effect of the post emergence herbicide on soybean, which appeared to recover completely by midseason.

The harvest area for maize was 4.5 m^2 corresponding to the area allotted to 20 plants in two rows. For soybean, two rows of 5 m row length (4.5 m^2) were harvested. The total harvested plant fresh weight was measured in the field and dry matter was determined by adjusting for the moisture content. Maize ears were dried, shelled and weighed for grain yield on a dry weight basis after taking observations on cob length, number of kernel rows per ear, and number of ears/20 plants. Soybean was threshed using a mechanical thresher and weighed to determine grain yield on a dry weight basis.

3.3.4 Statistical analysis and model building

Observations were adjusted to remove block effects, calculated using the replicated treatments. An analysis of variance was performed for all the variables combined over three environments using the SAS general linear model (GLM) procedure (SAS Institute Inc. 1986). Statistical analysis of grain yield and dry matter variables were based on gram per meter row length. A stepwise procedure was followed in the model-building process to determine the appropriate regression model to account for the effects of environment, soil phosphorus, system and their interactions. Phosphorus levels in the soil solution were transformed with natural logarithms before taking the polynomials. First the main effects P level, systems and their interactions were tested using the appropriate error. Main effect of target P level was then partitioned into linear and quadratic effects. Lack of fit of the linear and quadratic effects were also tested using the appropriate error terms. Differences between sites, years at Poamoho, cropping systems (Sole crop Vs Intercrop and between intercrops), and their interactions were partitioned into single-degree-of-freedom and tested using the appropriate error terms from the analysis of variance. A linear regression model was thereby developed for maize and soybean using effects that accounted for the phosphorus response, system differences, and the environmental variability (Table 3). The model was used to generate predicted yields of sole crops and intercrops at different P level for each environment. The predicted yields calculated per square meter of land area were used in the subsequent analysis. The phosphorus response of the intercrops was characterized with external phosphorus requirement (Fox 1981) calculated from the predicted yield.

Table 3. Regression model parameters for predicted grain yield (g m^{-1} row) and dry matter (g m^{-1} row) of corn and soybean across P levels, systems and environments. Effects were determined by hypothesis test (P<0.05). Lack of fit was no larger than the appropriate experimental errors.

Effects	Regression Coefficients	
	Yield	Dry matter
Maize		
Intercepts	467.52	1525.54
Kauai Vs Poamoho (KVP)	50.85	205.73
Poamoho Vs Poamoho (PVP)	222.78	607.96
Log(P)	24.05	77.71
Sole Vs Intercrop (SVI)	-8.68	-42.10
Soybean		
Intercepts	107.27	293.08
Environment		-73.15
Log(P)	5.54	16.40
Systems	-45.78	-93.78
Environment by system	-24.92	-35.23
Log(P)*system	-6.48	-11.59

Land Equivalent Ratio and Competitive Ratio (Willey and Rao 1980) were used as the basis for estimating advantage of intercrops over their component sole crops and the relative competitive ability of the intercrop components respectively. For the calculation of LER and Partial Land

Equivalent Ratio (PLER) the sole crop reference yield was taken from the same nutrient levels as the intercrop. PLER was calculated as the ratio of intercrop yield to that of sole crop and LER as the sum of maize and soybean PLER's. Competitive Ratio (CR) was calculated as the ratio of component PLER, corrected for the proportions in which the crops were initially planted. The density correction factor for maize CR was 1.0 (the densities were the same in the sole crop and intercrop) and for soybean was 0.5 (intercrop soybean had half the density of sole crop soybean). CR has been shown to be useful in (i) comparing the competitive abilities of different crops, (ii) measuring competitive change within a given combination subject to an experimental treatment, (iii) identifying plant characters associated with competitive ability, and (iv) determining competitive balance between components most likely to give maximum yield advantages (Willey and Rao 1980).

3.4 RESULTS

Maize cob length, number of rows per ear, 100 grain weight and harvest index increased with higher soil solution P concentrations. The responses ($\partial Y/\partial P$) were proportional to the inverse of the P level and were similar in sole crop and intercrop systems. The pattern of response was not affected by environments for all the above variables except harvest index (appendix 1.3). However maize harvest index in Poamoho 1988 was lower than in Poamoho 1989 (Table 4a).

Table 4a. Mean yield, yield components, and harvest index of sole and intercrop maize within three environments.

Year/ Systems	Number ear pl^{-1}	Ear Length cm ear^{-1}	Number row ear^{-1}	100 Grain wt. g	Harvest Index	Grain Yield g pl^{-1}
Kauai 1987						
Sole maize	0.95	12.12	11.72	32.11	0.32	80.97
Maize/rice	0.97	11.46	11.61	31.62	0.34	73.57
Poamoho 1988						
Sole maize	0.86	12.08	13.38	22.37	0.23	61.24
Maize/rice	0.85	10.85	13.12	21.94	0.24	49.54
Maize/soyb	0.88	11.64	13.29	21.11	0.26	57.15
Poamoho 1989						
Sole maize	1.00	18.52	13.57	31.36	0.31	169.44
Maize/soyb	1.00	18.25	13.81	31.09	0.31	167.60
CV (%)	6.10	11.10	4.70	4.90	12.20	15.30

Analysis of variance indicated a difference between sole and intercrop soybean grain yield, total dry matter, 100 seed weight and harvest index (Appendix 2). The harvest index for sole and intercrop soybean was affected by environment (Appendix 2.3, Table 4b).

Table 4b. Grain yield, dry matter, 100 grain weight, and harvest index of sole and intercrop soybean within two years at Poamoho.

Year/ Systems	Grain yield g pl^{-1}	Dry matter g pl^{-1}	100 Grain wt. g	Harvest Index
Poamoho 1988				
Sole soybean	9.18	25.09	17.34	0.36
Soybean/maize	6.59	19.86	15.97	0.33
Poamoho 1989				
Sole soybean	10.09	20.17	20.74	0.50
Soybean/maize	1.61	4.11	15.22	0.39
CV (%)	23.24	21.70	6.29	12.32

Intercrop maize grain yield ($plant^{-1}$) was reduced an average of 9% at Kauai and 19% at Poamoho 1988 by intercropping with rice. But, when maize was intercropped with soybean the reduction was an average og 7% in 1988 and only 1% in 1989 at Poamoho. The mean reduction in measured intercrop soybean grain yield ($plant^{-1}$) due to competition was 28% in 1988 and 84% in 1989.

The maize harvest index response to soil P was affected by environment (Fig. 1). Harvest index of soybean increased with an increase in soil P level only in the 1988 sole crop (Fig. 2).

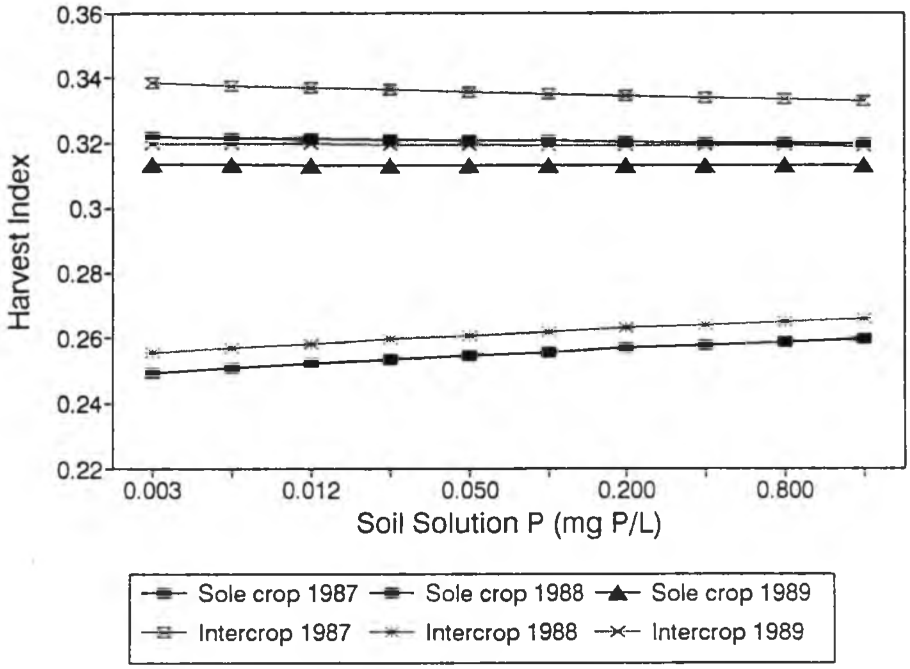

Figure 1. Effect of soil P level on harvest index of maize in each environment. Effects were identified by hypothesis testing (P< 0.05). Lack of fit of regression model was no greater than the appropriate experimental errors.

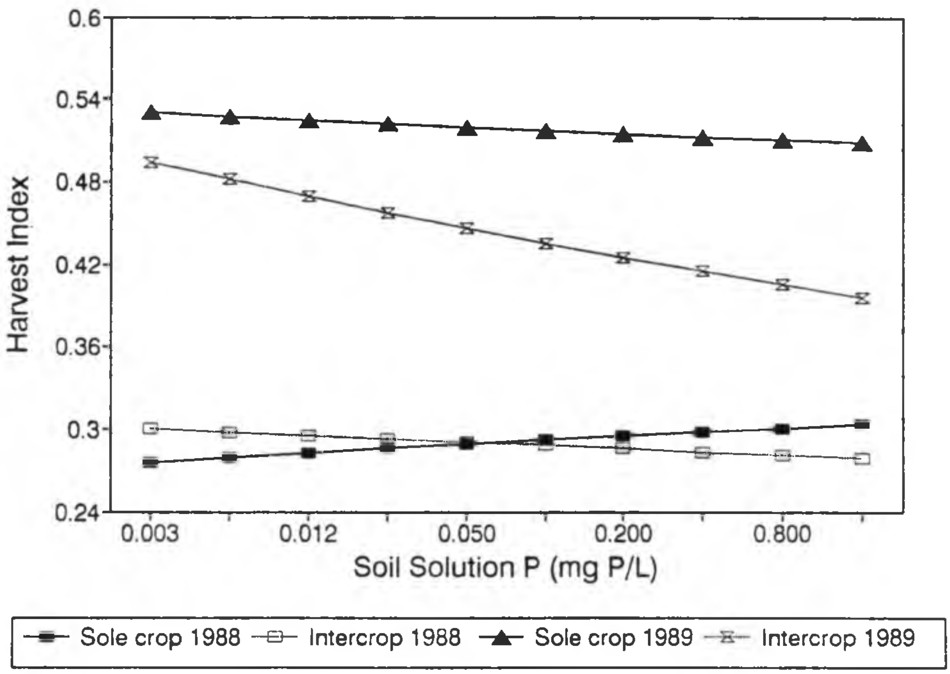

Figure 2. Effect of soil P level on harvest index of soybean in each environment. Effects were identified by hypothesis testing (P<0.05. Lack of fit of regression model was no greater than the appropriate experimental errors.

3.4.1 Combined analysis of grain yield and dry matter

The results of the combined analysis of variance for grain and dry matter yields of maize and soybean are presented in Tables 5a and 5b. Table 3 contains the regression coefficients for the yield response models.

Not only were the two sites, Kauai and Poamoho, different but also the two seasons at Poamoho. Environment was the most important source of variability for dry matter production in maize. There was a linear response to log(P) for both maize and soybean. A nonsignificant lack of fit established the linear effect (Table 5a and 5b).

Table 5a. F ratio from analysis of variance for maize grain and total dry matter yields (g m^{-1} row).

Source of variation	df	Yield	Dry matter
Total	117		
Kauai Vs Poamoho (KVP)	1	22.46 **	27.63 **
Poamoho 88 Vs Poamoho 89 (PVP)	1	229.49 **	120.09 **
Rep(Environments)	6	(17579.23)	(258444.24)
Phosphorus level	9	5.58 **	5.01 **
Log(P)	1	36.78 **	35.41 **
Lack of fit	8	1.68	1.22
Environment*P level	18	1.00	1.41
Rep(Environment*P level)	14	(4759.58)	(51244.30)
Sole Vs Intercrops (SVI)	1	4.97 *	12.46 **
Intercrop Vs Intercrop (INVIN)	1	3.39	1.76
KVP*SVI	1	0.22	0.01
PVP*SVI	1	0.42	2.95
P level*System	18	0.44	0.55
Environment*P level*System	14	1.51	1.77
Error	38	(3500.02)	(31582.98)

Table 5b. F ratio from analysis of variance for soybean grain and total dry matter yields (g m^{-1} row).

Source of variation	df		Yield	Dry matter
Total	59			
Environment (ENV)	1		2.82	9.74 *
Rep(Environment)	4		(3128.94)	(28175.66)
Phosphorus level	9		2.56	1.25
Log(P)		1	7.87 *	6.54 *
Lack of fit		8	1.89	0.59
Environment*P level	9		2.19	0.91
Rep(ENV*P-levels)	8		(325.29)	(5351.61)
System (SYS)	1		290.94 **	216.27 **
Environment*System	1		59.88 **	39.18 **
P level*System	9		2.23	3.19
Log(P)*System		1	15.21 **	14.95 **
Lack of fit		8	0.61	1.97
Environment*P-level*System	5		1.65	3.76
Error	16		(283.54)	(1316.63)

*, ** F ratio significant at 0.05 and 0.01 level.
Numbers in the parenthesis are mean square errors.

Maize yields of both grain and total dry matter were higher in the sole crops than the intercrop maize but there was no difference in maize yields from the two intercrops (maize/rice and maize/soybean). Across environments and soil P levels, the reduction in maize grain and dry matter yield due to intercropping was less than 10% (based on predicted yield) in any particular environment. The response of maize grain and total dry matter yield to soil solution phosphorus, $\partial Y/\partial P$, was the same for all systems and environments. The regression of yield on the natural logarithm of soil P gave the same slope but different intercepts in the three environments and in sole crop versus intercrop.

Soybean grain and total dry matter yields differed by environment and system (Table 5b). System differences were affected by environment, and P response was different for sole and intercrop soybean. The P response in soybean was more sensitive to environmental variability than maize. The slope of the P response for intercrop soybean was negative with a marginal decrease in yield from lower to higher P levels. The intercrop legume component was more sensitive to changes in the environment (i.e. % yield change from 1988 to 1989) than intercrop maize.

3.4.2 External P requirement of intercrop components

As expected, the external phosphorus requirements, based on predicted yield from the regression model, were variable in different environments. The external P requirement for intercrop maize was 0.1 mg/L at Kauai. At Poamoho it was 0.3 mg/L in 1988 and 0.05 mg/L in 1989. Maize yields both in intercrop and sole crop increased with an increase in soil phosphorus concentrations (Appendix 1.1). The external P requirements of intercrop maize were always similar to the sole crop and the differences were negligible in all the environments (Fig. 3). The external P requirement for sole crop soybean was 0.4 mg/L in 1988 and 0.3 mg/L in 1989 at Poamoho. The P response curve for intercrop soybean was a decreasing curve, and as such, it depicts more of the competitive effect of maize rather than P response (Fig. 4).

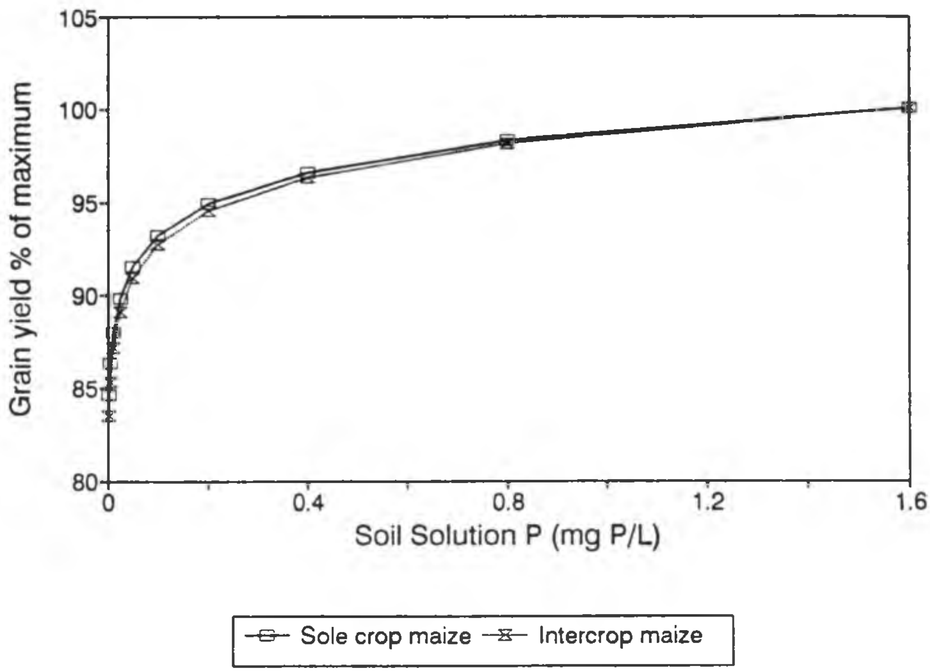

Figure 3. Response of maize yield to phosphorus, relative to maximum expected yield (mean yields of three environments, Kauai 1987, Poamoho 1988 and 1989).

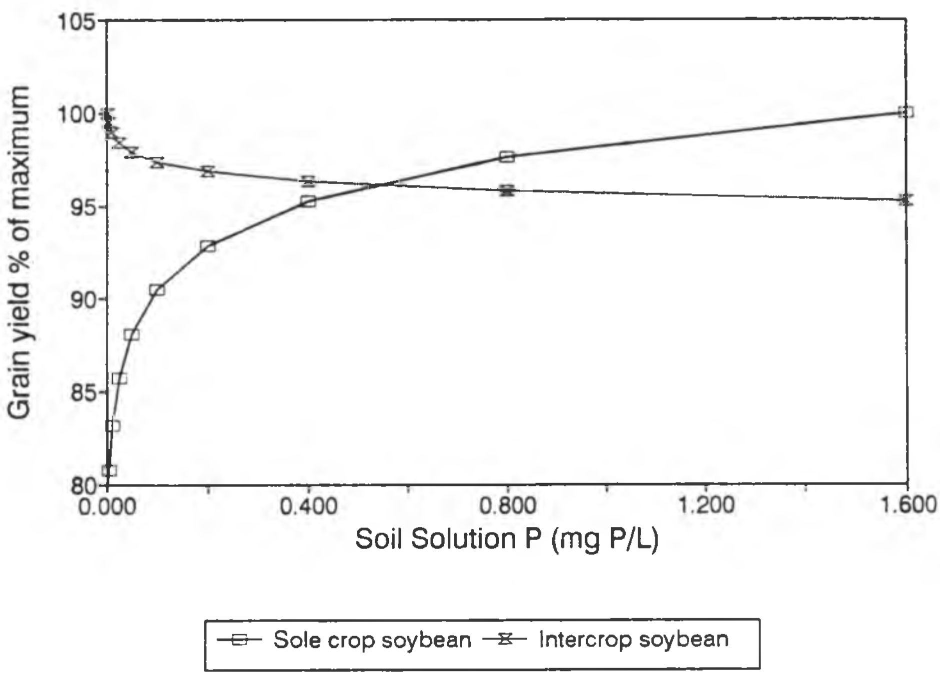

Figure 4. Response of soybean yield to phosphorus, relative to maximum expected yield (mean yields of two environments, Poamoho 1988 and 1989).

The range in the predicted intercrop soybean yield from lowest to highest P levels was only 3% in 1988 and 7% in 1989, whereas for the sole crop it was 25% in 1988 and 18% in 1989 indicating the cropping system by log(P) interaction and the overall competitive effect of maize. The response in intercrop soybean indicated more of the effect of companion maize than the direct effect of P on the soybean.

3.4.3 Partial LERs of maize and soybean

Competition in intercropping reduced maize grain and dry matter yields only by 3 to 10% across environments at different P levels as indicated by PLERs (Fig. 5a and 5b). The range of soybean PLERs across environments and phosphorus levels were large compared to maize. The yield reduction in the intercrop soybean were 10 to 34% in 1988 and 74 to 80% in 1989 across P levels. In 1989, maize grew vigorously and effectively suppressed the intercrop soybean. The difference in maize PLER at the lowest and highest P levels was very small in all the environments. A trend of relatively greater decline in intercrop soybean than intercrop maize with increased phosphorus levels was evident. However this decline was sharper in the low productivity environment in 1988. Maximum PLER for maize was attained at higher P concentrations, and the opposite was true for soybean.

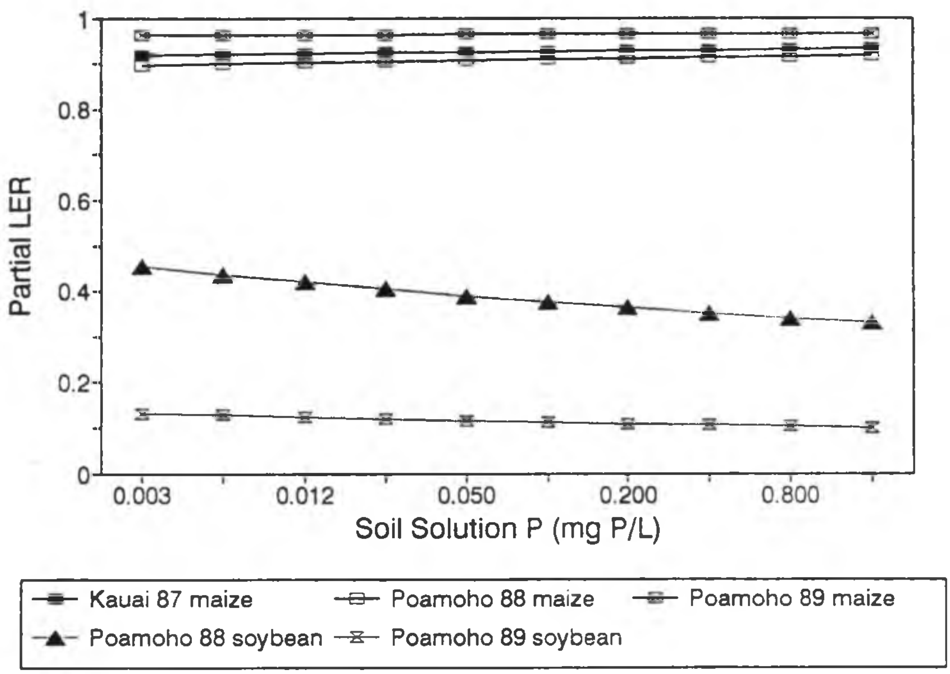

Figure 5a. Partial Land Equivalent Ratio (PLER) based on predicted grain yield (Table 3) as affected by soil solution P in each environments.

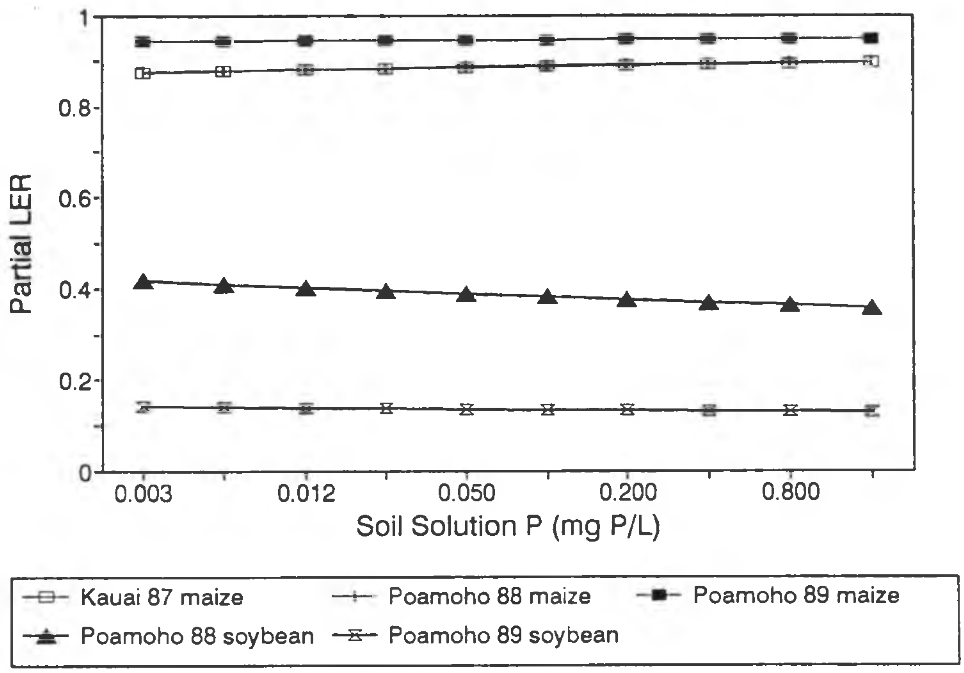

Figure 5b. Partial Land Equivalent Ratio (PLER) based on predicted total dry matter (Table 3) as affected by soil solution P in each environments.

3.4.4 LER and CR

LERs for maize soybean intercrops were greater than unity for all P concentrations at Poamoho (Fig. 6). Land utilization efficiency declined with soil P levels.

In general, maize was more competitive than soybean, with CR (based on grain yields) ranging in magnitude of 0.9 to 4.8 times across environments and P levels (Fig. 7a). The competitiveness of maize increased with higher soil solution P concentration. In 1988, maize grain yields were low and maize was less competitive, which corresponded with high efficiency (LER = 1.25 to 1.35). But in 1989, the vigorous growth of maize smothered soybean at high P concentration, and the efficiency was marginal (LER = 1.06 to 1.09). In both extreme cases, higher land use efficiencies were achieved at lower P concentrations.

The basic relationships found for LER and CR based on grain yield were also true for total dry matter yield (Fig. 6 and 7b).

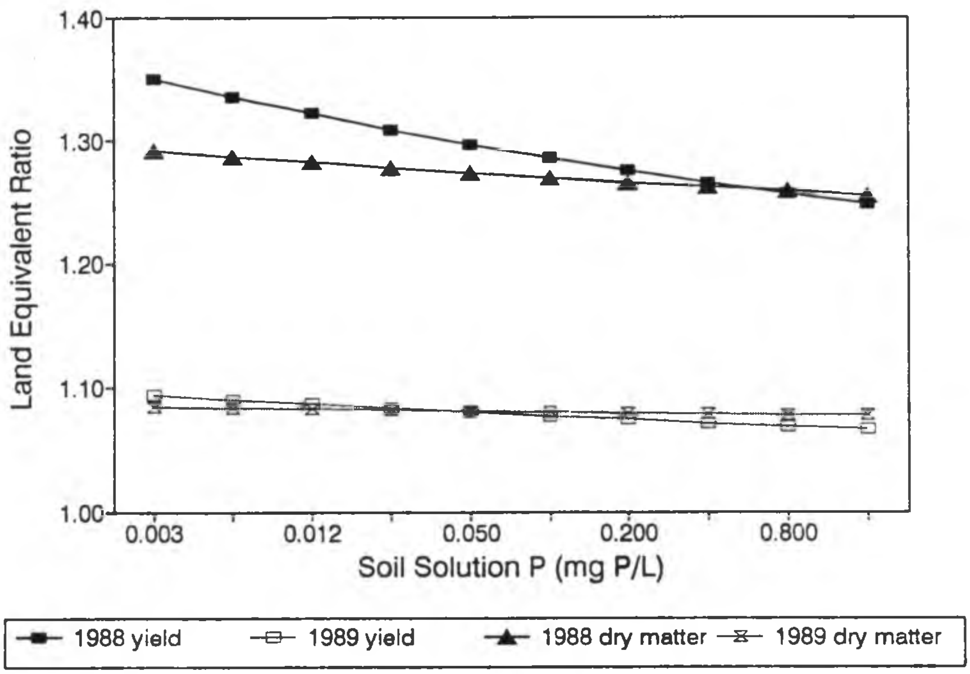

Figure 6. Effect of soil solution phosphorus levels on Land Equivalent Ratio (LER) at Poamoho.

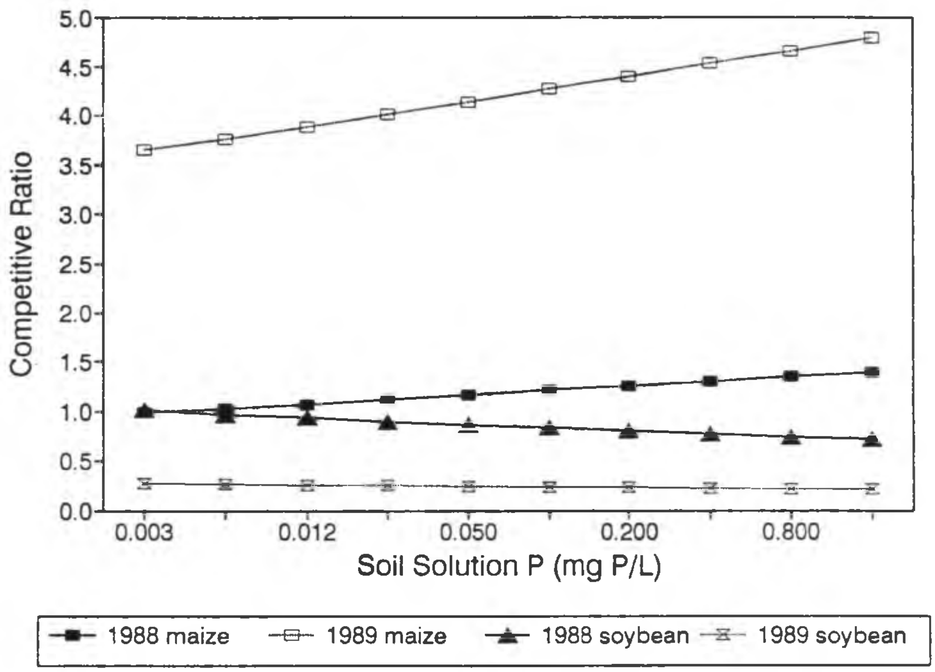

Figure 7a. Effect of soil solution phosphorus levels on Competitive Ratio (CR) of maize and soybean at Poamoho based on grain yield.

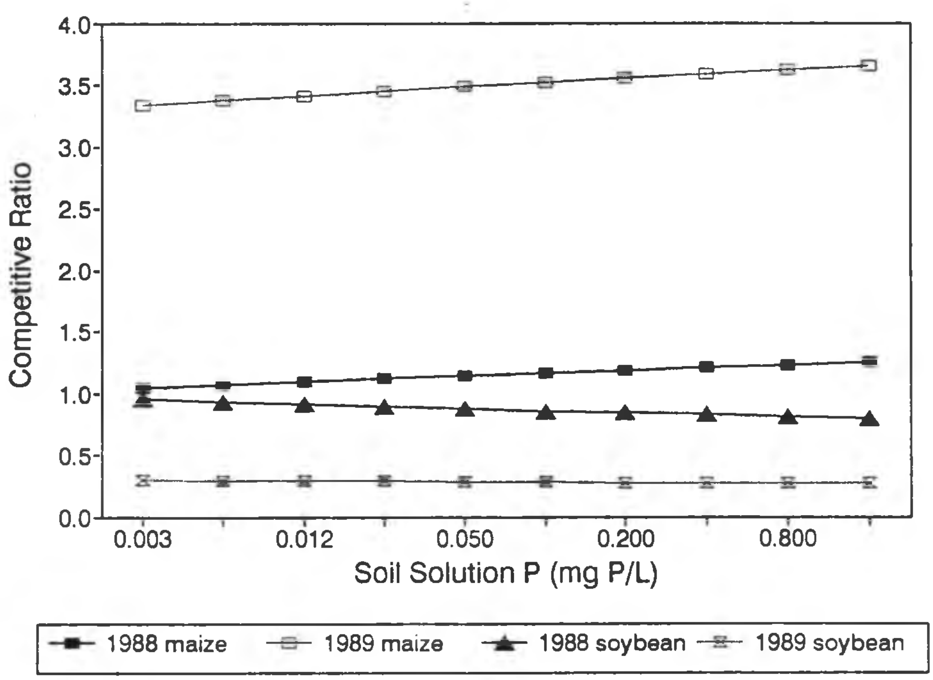

Figure 7b. Effect of soil solution phosphorus levels on Competitive Ratio (CR) of maize and soybean at Poamoho based on total dry matter yield.

3.5 DISCUSSION

Separate analysis of variances within each environment indicated that the intercrop maize grain yields were no different than the yields in the sole crop. The only species to reduce maize dry matter yield in the intercrop was rice in Kauai 1987 (based on Duncan's multiple range test; result not shown). The combined analysis indicated higher grain and dry matter yield of maize in sole crops than in intercrops. The combined analysis of variance partitioned the effect of system into (i) sole crop versus intercrop (intercrop being the mean of maize/rice and maize/soybean) (ii) the maize/rice intercrop versus maize/soybean. The first effect was identified to be real (i.e. 3 to 10% yield reduction due to intercropping) but not the second effect. These inferences contradict those from the separate analysis of variances within each environment, reflecting the different hypothesis tests and the level of precision associated with each. Apart from the statistical significance, the maize yield reduction of 3 to 10% due to intercropping may not be agronomically significant, especially considering the very large year to year variation in absolute yields.

In the literature there are more cases of intercrop maize producing the same as sole crop maize (Mohta and De 1980, Chang and Shibles 1985, Ezumah et al 1987) than otherwise. Ahmed and Rao (1982), based on international multilocation testing of maize/soybean intercrops reported there was no significant difference in maize yield between sole and intercropping in nine out of fourteen experiments. The replacement series experiments reported by Ahmed and Rao contained by design lower intercrop maize densities than sole crop maize. Consistently high PLERs for maize in my experiments, encompassing a wide range of soil P status and large productivity variation, is in line with most of the above results. This demonstrated the dominance of the higher competitive maize plant across different environments and nutrient levels. If the intercrop maize population density is the same as sole crop maize, only a moderate reduction in intercrop maize yield would be expected. A drastic reduction in intercrop maize would occur only in the extreme cases of intercrop soybean being highly favored by the environment or by the design. Because of this, the strategy of many subsistence farmers to achieve some additional yield of an intercropped legume, like soybean, with only a moderate reduction in maize yield is reasonable. The effect of interspecific competition was very moderate in reducing intercrop maize yields but severe in reducing intercrop soybean yields.

The concept of external P requirement has been extensively used to characterize P response and requirement in sole crop situations. P response of sole and intercrop maize being same, the external P requirement of intercrop maize is similar to that of sole crop maize.

The response pattern of soybean yield was not similar to maize. Highest intercrop soybean yields were achieved at the lowest P concentrations and vice versa for sole crop. The difference between the lowest and highest intercrop soybean yield was small compared to the difference in the sole crops. Unlike sole crops, the grain yield response to log(P) in intercrop soybean depicted a negative slope due to interference by the maize crop. The same concept of external P requirement was extended to the intercrop situations where yields are reduced by competition. Since the intercrop soybean yield decreased with P application associated with increased growth of maize, the external P requirement for intercrop soybean in such cases is the soil solution P level at which 95 percent grain yield is achieved across a decreasing curve.

Large variation exists in published results on relative yields and intercrop performance at different nutrient levels. Remison (1978) reported that N and P fertilizer application had no effect on relative yield total. The relative yield total in all the cases was greater than two, the highest being 2.69. Contrasting results for nitrogen have been reported (Ofori and Stern 1986, 1987; Ahmed and Rao 1982). In my experiment the relative advantage of intercropping, as indicated by LER, decreased with increasing soil fertility levels. But because of the linear response to log(P), cumulative absolute yield may be much higher at high P concentrations. On the basis of LER and CR, an inverse relationship operated between intercropping efficiency (LER) and the competitiveness of the cereal component. Aggarwal and Sidhu (1988) observed decreased LER and increased maize competitiveness with nitrogen application. Chang and Sibbles (1985) have reported similar results for nitrogen levels.

The magnitude of advantages due to intercropping in any intercrop combination are dependent upon the competitive relationships of the component crops. These relationships are affected by climatic and soil fertility levels, making it difficult to predict intercrop performance in new environments. Regression models, built using a stepwise statistical procedure as presented in this chapter, are effective tools in summarizing the yield of component crops to evaluate intercrop performance based on real effects only.

Although the effect of environment is large relative to other effects, a qualitative prediction of intercrop performance is possible. Based on my experiments and the published literature, greatest LERs should occur in low productivity environments when maize is least competitive. The extent of interference and the nutrient response of each intercrop component will influence the intercrop performances in a particular environment.

These results have important implications for the management of intercrops in subsistence agriculture. Fertilization of intercrop mixtures has been very problematic due to different requirements of mixture crops (Wahua 1983). The morphological and physiological differences of component crops that are the basis of advantage create difficulties in the fertility management. Subsistence farmers have access to very little fertilizer inputs. The relevant question is not maximum yields but how to achieve maximum efficiency.

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4.

EFFECT OF PHOSPHORUS AVAILABILITY ON GROWTH, P UPTAKE, AND EFFICIENCY IN INTERCROPS IN DIFFERENT ENVIRONMENTS

4.1 SUMMARY

While there is an abundance of experimental results on increased productivity of intercrop systems, the interpretations are limited to the effect of increased crop diversity on reducing insect and disease attack, and increasing the efficiency of resource utilization. There is a dearth of information on how intercrops respond to varying levels of P availability leading to greater efficiency. The present experiment was conducted at the University of Hawaii to evaluate a maize/soybean intercrop system for periodic dry matter production, leaf P concentration and leaf properties. P uptake and its conversion efficiency were evaluated to determine whether the increased productivity of the mixture was only due to increased uptake of resources or efficient conversion to dry matter or grain yield by intercrop components under competition.

Growth of intercrop maize was no different than the sole crop for their periodic dry matter, P concentration, leaf properties and P uptake, but was profoundly affected by environment and P availability in the soil.

The response of intercrop soybean to environment and P level was more complex and differed from that of the sole crop. Interactions between environment, P level, and the

growth conditions of the companion maize determined the response of intercrop soybean. Soybean leaf properties, leaf tissue P concentration, and P uptake were influenced by environment, P levels, and system (intercrop versus sole crop) and their interactions.

The increased productivity of the intercrop combination was associated with increased extraction of soil phosphorus. In low-input subsistence agriculture, the accelerated P mining -- the faster removal of limited soil P -- may cause the intercrop systems to be less sustainable.

4.2 INTRODUCTION

The differential ability of plant species, and even cultivars of the same species, to extract and utilize soil phosphorus is well documented. Plant species grown in solution culture required different P concentration for optimum growth (Asher and Loneragan 1967). Some species required 0.03 mg/L, while others required 25 times more (Fox 1981). Alt and Ladbush (1984) observed a 50% reduction in lettuce yield on a very P deficient soil whereas spinach and cabbage yield were unaffected. It is clear that the quantity of P needed in the plant to produce a unit of dry matter will depend upon the genetic potential of species as well as P availability, which is influenced by soil type and climate.

When two crops are grown together as an intercrop, availability of P is expected to be affected by the overlapping of depletion zones around the roots of the same as well as different species. The competition for P by two species should also be dependent upon the combined demand for P and the amount of P in the soil solution which is the major factor controlling the flux of P to plant roots. Whether intercropping, with the greater demand or the expected faster depletion of the soil solution P, will result in a different uptake and efficiency of phosphorus at different P availability has not been investigated.

Very little is known about P competition in intercrops especially maize/soybean intercrops. It is generally expected that P concentration in leaves of the sole crop and intercrop are the same at the beginning of the growth cycle and any difference in concentration at later stages can be attributed to interference. Also, the total P uptake and dry matter accumulation by an intercrop combination can be expected to be greater than that of the sole crop throughout the growth stages. Results of Chang and Shibles (1985) are conclusive in this regard for a maize/cowpea intercrop in a replacement series experiment.

Extensively cited data of Dalal (1974) indicated that total P uptake (6 and 16 weeks after planting) by sole crop maize was greater than a maize/pigeonpea intercrop. The intercrop pigeonpea P uptake was less than that of the sole crop at 6 and 16 weeks after planting, but at 24 weeks there was no difference between sole and intercrop P uptake. The soil P status remained unaffected 16 weeks after planting. Srinivasan and Ahlawat (1983) also recorded no difference in soil P status between sole crop pigeonpea and intercrop with green gram or sorghum. Wahua (1983) observed no difference between P uptake (up to 50 DAP) of sole and intercrop maize; however, at higher fertility levels uptake by the sole crop was greater than intercrop and the reverse was true at lower fertility levels. The uptake by intercrop cowpea was much lower than the sole crop 40 days after planting. CIAT

(1980) reported lower P concentration in leaves of intercropped cassava and cowpea compared to sole crops. Mason et al (1986) observed that intercropping cassava with cowpea reduced the P concentration in leaf, stem and storage roots of cassava at early growth stages (till 80 days after planting) but not after. P concentration was not reduced when cassava was intercropped with peanut throughout the growth stages. The P concentration of sole and intercrop legume plant parts remained unchanged except for peanut pods; however, total uptake by the intercrop was greater than that of the sole crops resulting in rapid mining of soil resources in the intercrop. Most of the experiments reviewed were conducted with adequate P fertilization, and none of them dealt with intercrop response to P across a range of P levels in different environments.

Intercrop systems have been advocated to be more efficient in land use compared to sole crop systems, and therefore suitable and desirable in sustainable agriculture. It is unclear whether the increased efficiency is due to only more resource extraction or to more efficient conversion of resources to dry matter and marketable yield. The present paper deals with the dry matter accumulation, leaf area, leaf P concentration, and total P uptake by maize and soybean in maize/rice and maize/soybean intercrop systems. The P uptake and conversion efficiency of intercrops will be discussed in relation to phosphorus levels in the soil solution under different environments with the following objectives:

1. To compare the growth in dry matter and leaf properties of maize and soybean in maize/soybean and maize/rice intercrops with sole crops under different environments.

2. To quantify the effect of interspecific competition on uptake of phosphorus under different P availability.

3. To evaluate P conversion efficiency of intercrops compared to sole crops.

4.3 MATERIALS AND METHODS

4.3.1 Location of experiment, site and soil description

Two sites in Hawaii, having contrasting soil and climatic conditions, were utilized to conduct an experiment in three environments (Table 1, Chapter 3). Permanent plots were utilized for the intercropping experiments, where ten target phosphorus concentration in soil solution have been established since 1971. The field trial at Wailua Experiment Station, Kauai, was planted in 1987 on a highly weathered clayey, sesquic, isothermic, Anionic Acrudox. Two field trials were conducted during the summers of 1988 and 1989 at the University of Hawaii Poamoho Experiment Station on a silty clay of the Wahiawa series classified as clayey, kaolinitic, isohyperthermic, Rhodic Eutrustox.

4.3.2 Treatments and experimental design

Main plots of ten target P levels (0.003, 0.006, 0.012, 0.025, 0.05, 0.1, 0.2, 0.4, 0.8, 1.6 mg P/L in soil solution) were laid out in an augmented block design (Federer 1956). The target P levels in soil solution were achieved using phosphorus sorption techniques (Fox and Kamprath 1970). Appropriate amounts of P fertilizer in each treatment were applied as triple superphosphate before the last tillage operation to achieve the targeted levels of P in soil solution. In Kauai the four middle P levels (0.025, 0.05, 0.1 and 0.2 mg P/L) were replicated three times, the four extreme levels (0.003, 0.006, 0.8 and 1.6 mg P/L) occurred only once and the remaining two (0.012 and 0.4 mg P/L) were replicated twice. Each of 20 main plots (12.19 m by 9.14 m) contained each of the three sole crops (maize, rice and soybean) along with maize/rice and maize/soybean intercrops.

The treatments and experimental design at Poamoho were slightly different from Kauai. Four P levels, 0.012, 0.025, 0.050 and 0.100 mg P/L, were replicated three times and the rest of the unreplicated treatments constituted the 18 main plots (15.24 m by 5.49 m). Each main plot in 1988 contained one of the sole crops (maize, rice or soybean) and the two intercrop patterns. In 1989, main plots contained the maize/soybean intercrop with both maize and soybean sole crops (Table 2, Chapter 3).

Maize spacing was 0.90 m by 0.25 m for both sole crop and intercrop. Sole crop rice was planted in a row spacing of 0.30 m at a seeding rate of 100 kg/ha. Two rows of rice were planted between two rows of maize in the maize/rice intercrop with a seeding rate of 66.6 kg/ha. Sole crop soybean was spaced at 0.45 m by 0.10 m. Intercrop soybean was spaced at 0.90 m by 0.10 m apart as alternate rows with maize so that it had half the population of sole crop soybean. Nitrogen from urea and potassium from potassium chloride were supplied at a rate of 150 kg/ha each before planting. Soybean was inoculated with rhizobium. A drip irrigation system supplied water uniformly at Poamoho, but the Kauai experiment was rainfed.

Destructive plant samples were taken from each subplot (cropping system within a P level) at different growth stages to determine the growth of maize and soybean. Three plants of maize and a 0.50 m row length of soybean were harvested for leaf area and fresh weight determination. Green leaves were separated and leaf area was measured using a LI-COR 3100 leaf area meter before drying the sample for dry matter determination. The sampling dates were not exactly the same in all the environment (Table 6).

Table 6. Sampling schedule for leaf punch, leaf dry matter and total dry matter in three environments. (Fourth sample was taken before harvest).

Environments	Planting date	Samples 1st	2nd	3rd	4th
		Days after planting (DAP)			
Kauai 1987	Nov.17	25	50	90	130
Poamoho 1988	May 17	27	50	77	113
Poamoho 1989	June 8	27	50	70	116

Periodic leaf punch samples from four separate randomly selected plants within subplots of each crop were analyzed for P concentration using the Mo blue method (Murphy and Riley 1962). Final harvest P concentration of plant and grain samples along with observed values of the total dry matter and grain yield were utilized to calculate P uptake and efficiency. P uptake was calculated as the product of % P and total grain and dry matter. The P efficiency was calculated as grain or dry matter produced per unit of P uptake.

4.3.3 Data analysis

Observations were adjusted to remove block effects, calculated using the replicated treatments. For maize and soybean an analysis of variance was performed on variables such as dry matter (g m^{-2}), leaf dry weight (g m^{-2}), leaf area index, leaf area ratio (cm^2 g^{-1}), and specific leaf area (cm^2 g^{-1}) within each environment to establish differences in sole and intercrop system and their response to soil solution P.

An analysis of variance was performed on leaf punch P concentration combined over three environments using SAS general linear model (GLM) procedure (SAS Institute 1986). A stepwise procedure was followed to establish effects of days after planting, environment, phosphorus level and system. Linear and quadratic effects of the natural logarithm of target soil solution P and their interactions with systems and environments were tested using appropriate error terms. Lack-of-fit of the linear and quadratic effect were also tested using appropriate error terms. The effects of days-after-planting and its interaction with phosphorus, system, and environment were also evaluated. P uptake was calculated as the product of P concentration in grain and grain yield plus the product of P concentration in stover and stover yield. Regression models for maize and soybean were developed which predicted P uptake in sole and intercropping in each environment. All subsequent analyses of P use efficiences and Land Equivalent Ratio based on P uptake were carried out using the predicted values.

4.4 RESULTS

Treatment means for dry matter, P concentrations, leaf area index, leaf area ratio, and specific leaf area averaged across P levels, are presented in tables 7 and 8. Analysis of variance tables are presented in appendices 3 to 8.

Table 7. Treatment means for dry matter (DM), percent P in leaf punch, leaf area index (LAI), and specific leaf area (SLA) of maize at different growth stages in three environments averaged over P levels. See analysis variance (Appendices 3 through 7) for level of significance.

Days after planting	Dry matter Maize	Dry matter M+R	Dry matter M+S	P in leaf punch Maize	P in leaf punch M+R	P in leaf punch M+S	LAI Maize	LAI M+R	LAI M+S	SLA Maize	SLA M+R	SLA M+S
	($g\ m^{-2}$)			(%)			($m^2\ m^{-2}$)			($cm^2\ g^{-1}$)		
Kauai 1987												
25	45	44		-	-		-	-	-	-	-	-
50	401	302		0.30	0.28		-	-	-	-	-	-
90	659	553		0.32	0.31		-	-	-	-	-	-
Harvest	1111	930		0.18	0.17		-	-	-	-	-	-
Poamoho 1988												
14	-	-	-	-	-	-	0.02	0.02	0.02	185	214	213
27	25	26	25	0.29	0.35	0.37	0.26	0.27	0.25	195	207	196
50	248	215	207	0.25	0.27	0.27	1.64	1.38	1.27	149	144	146
77	635	733	644	0.19	0.21	0.22	1.28	1.60	1.42	125	130	129
Harvest	1141	913	948	0.22	0.23	0.24	-	-	-	-	-	-
Poamoho 1989												
27	52	-	46	0.38		0.36	0.60		0.54	234		237
50	481	-	434	0.31		0.31	3.64		3.26	182		180
70	1094	-	987	0.32		0.32	3.66		3.53	152		162
Harvest	2385	-	2347	0.29		0.26	-		-	-		-

Maize:Sole crop maize; M+R:Intercrop maize/rice; M+S:Intercrop maize/soybean.

Table 8. Treatment means for dry matter (DM), percent P in leaf punch, leaf area index (LAI), and specific leaf area (SLA) of soybean at different growth stages in two environments averaged over P levels. See analysis of variance (Appendices 3 to 7) for level of significance.

Days after planting	Dry matter Sole	Dry matter Intercrop	P in leaf punch Sole	P in leaf punch Intercrop	LAI Sole	LAI Intercrop	SLA Sole	SLA Intercrop
	($g\ m^{-2}$)		(%)		($m^2\ m^{-2}$)		($cm^2\ g^{-1}$)	
Poamoho 1988								
27	63	29	0.34	0.27	0.48	0.24	297	313
50	345	118	0.49	0.41	2.84	1.02	352	358
77	856	326	0.28	0.31	2.84	1.02	258	274
Harvest	739	326	0.49	0.39	-	-	-	-
Poamoho 1989								
27	17	8	0.50	0.52	0.35	0.17	249	264
50	156	43	0.34	0.36	2.75	0.94	327	422
70	360	61	0.34	0.34	3.71	0.77	288	459
Harvest	571	118	0.23	0.22	-	-	-	-

4.4.1 Dry matter accumulation by intercrops

Maize dry matter accumulation was affected by intercropping in Kauai and Poamoho 1988 but not in Poamoho 1989 (Appendix 4). Soybean dry matter accumulation was reduced by intercropping in both years at Poamoho (Appendix 3).

Periodic dry matter of maize was predominantly affected by days after planting and soil P levels in all three environments (Appendix 4). The magnitude of reduction in intercrop soybean was more in 1989 as indicated by PLER (Fig. 8).

Response of dry matter to P, $\partial Y/\partial P$, was similar in sole crop and intercrop maize but was different for each date (log(P)*date interaction; Appendix 4). The system by date interaction was real only in two environments (Kauai 1987 and Poamoho 1988). The response to P and its interactions with system and date was dependent on the growth conditions of component crops. In Poamoho 1989, maize growth was vigorous and overcame any interference by companion soybean, which resulted in a similar response to P in the sole crop and intercrop. Sole and intercrop maize accumulated the same amount of dry matter over time as well (Appendix 4.3; Figs. 9 and 10). In Kauai and Poamoho 1988, maize growth was relatively low, and the system by date interaction had an effect (Appendix 4.1 and 4.2).

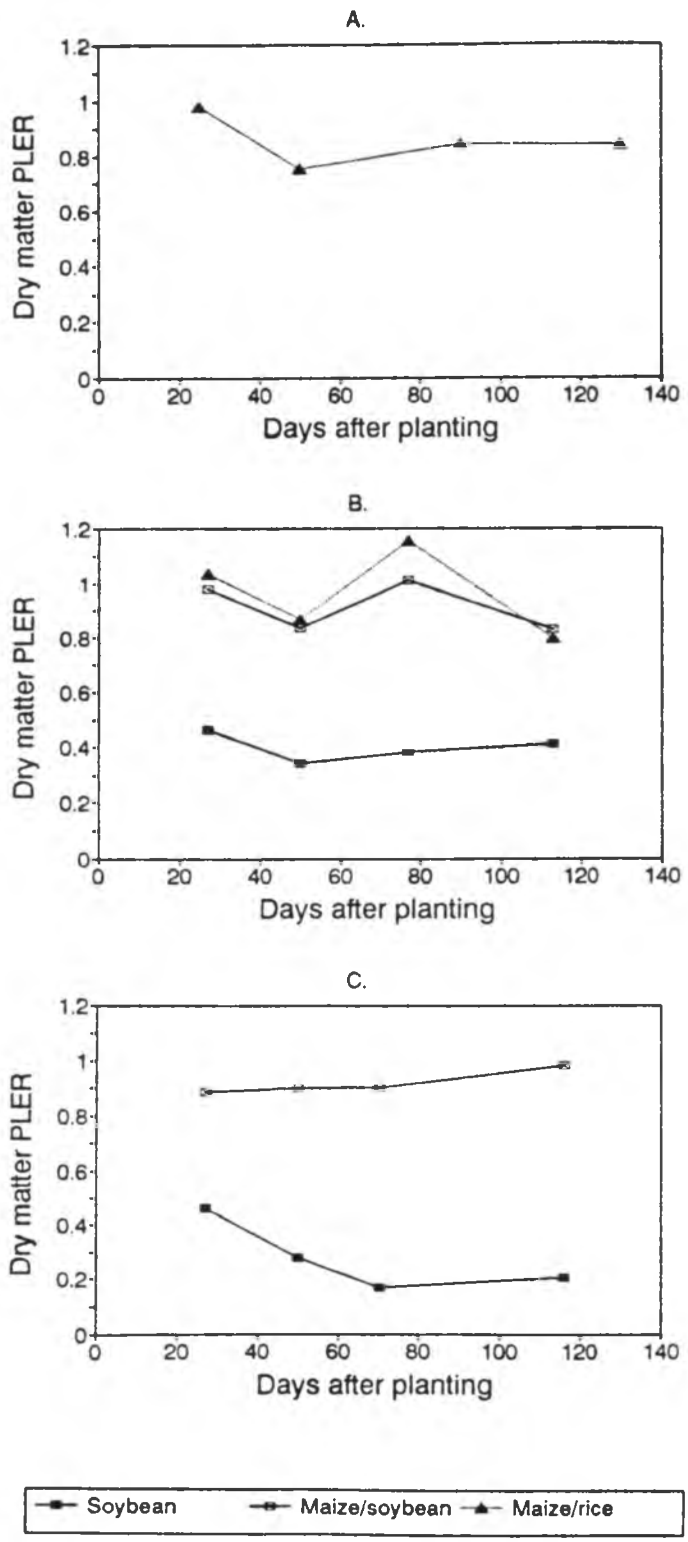

Figure 8. Partial Land Equivalent Ratio of maize and soybean at different growth stages at (A) Kauai 1987, (B) Poamoho 1988, and (C) Poamoho 1989.

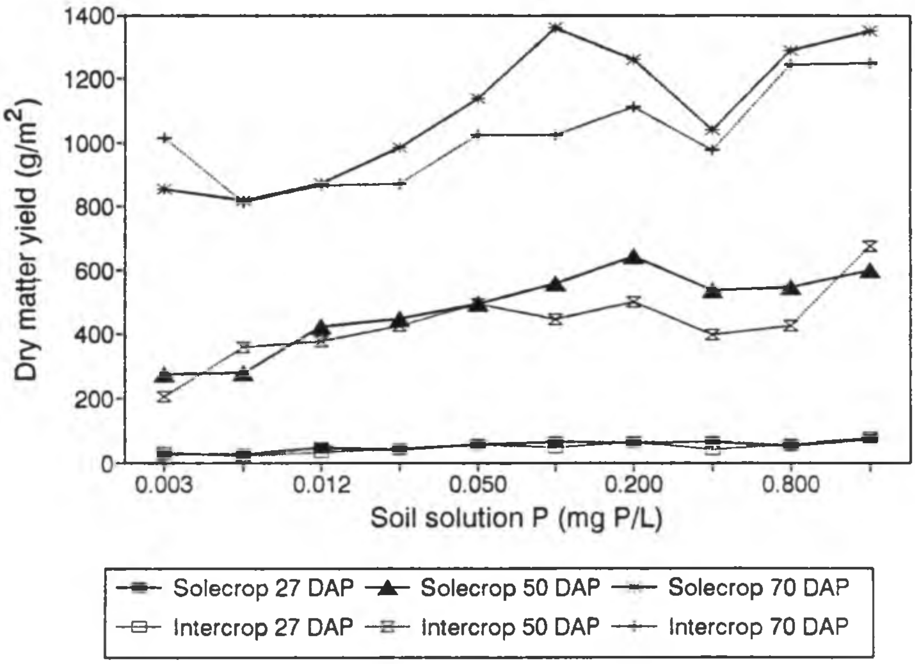

Figure 9. Dry matter production of sole and intercrop maize at different P levels and growth stages at Poamoho during 1989.

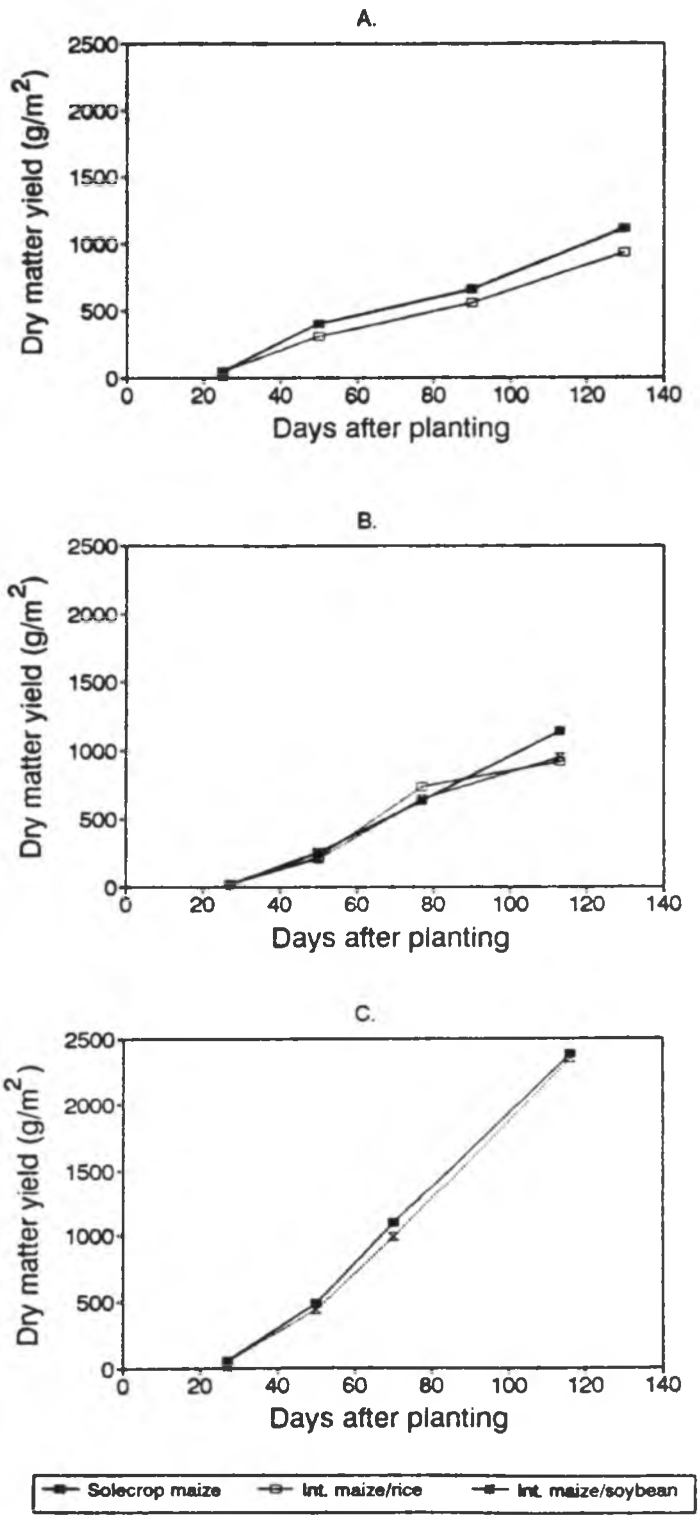

Figure 10. Growth in dry matter of sole and intercrop maize at different growth stages at (A) Kauai 1987, (B) Poamoho 1988, and (C) Poamoho 1989.

There was a linear response of soybean to log(P) in both environments but the response was different in sole cropping and intercropping (Appendix 3). The effect of competition on intercrop soybean by the companion maize crop was more evident at Poamoho during 1989 than during 1988, especially during the later growth stages at higher soil P levels (Fig. 11). As time during growth proceeded the benefit of additional soil P increased and the difference in sole crop and intercrop dry matter increased (Fig. 12). Soybean dry matter response to P was similar in both environments at different growth stages. Dry matter accumulation by intercrop soybean was less than the sole crop throughout the growth stages of the crop.

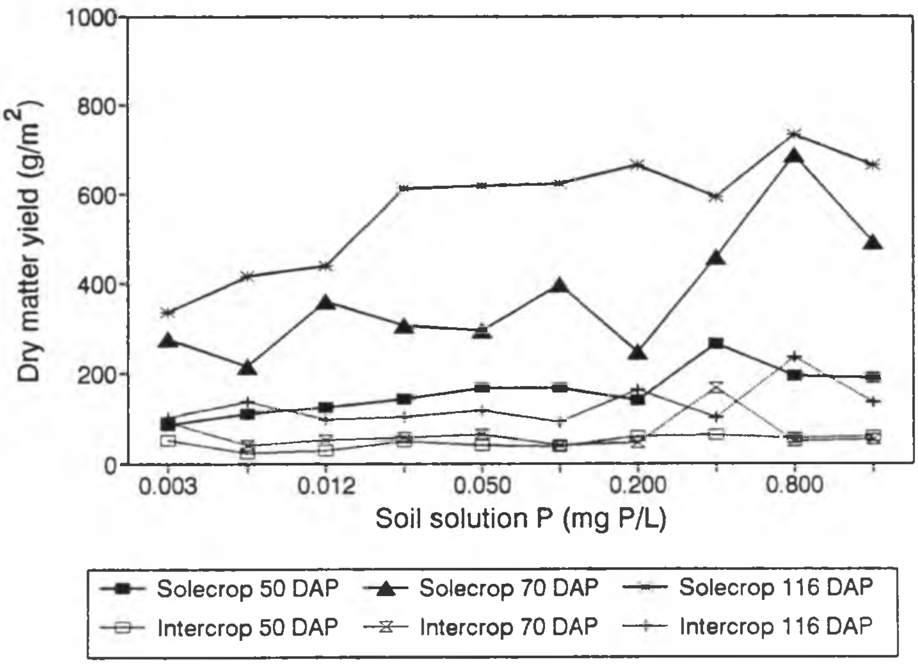

Figure 11. Dry matter production of sole and intercrop soybean at different P levels and growth stages at Poamoho during 1989.

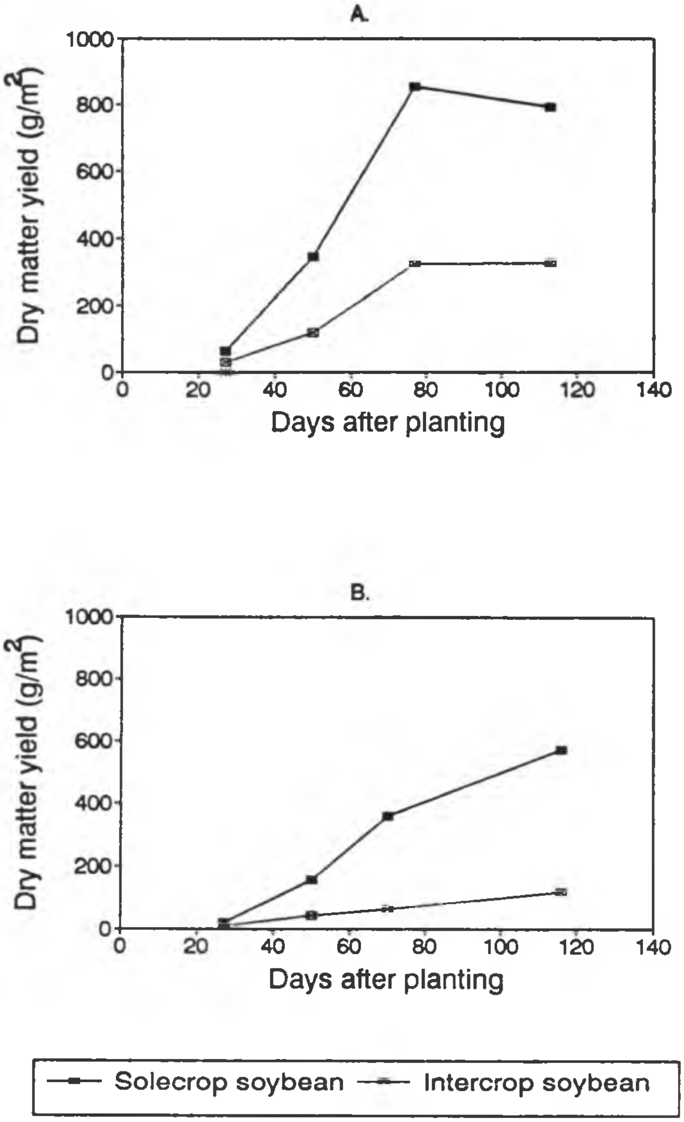

Figure 12. Growth in dry matter of sole and intercrop soybean at different growth stages at (A) Poamoho 1988 and (B) Poamoho 1989.

4.4.2 Leaf properties of intercrops

(i) Leaf area index (LAI)

There was a linear response to log(P) for maize and soybean LAI within both seasons at Poamoho but a quadratic response occurred only in 1988 for maize (Appendix 5.2 and 6.2). Not only was the response to P, d(LAI)/dP, the same for sole and intercrop systems, but the response was also similar at different dates for maize (Fig. 13). The LAI of sole and intercrop maize was the same within each date. LAI of intercrop soybean was reduced by intercropping (Appendix 6, Table 8). The response to P was different for the intercrop and the sole crop soybean in 1988 (Fig. 14), whereas LAI of sole crop and intercrop soybean was different within each date in 1989 (Fig. 15).

(ii) Leaf dry weight and specific leaf area (SLA)

There was no difference in leaf dry weight and specific leaf area (leaf area/leaf dry weight) between sole and intercrop maize (Appendix 5.1 and 5.3). Specific leaf area of maize declined with the advance of growth stage in both year (Table 7). Maize leaf dry weight increased with increased in P level in both the years. Specific leaf area of maize decreased with increase in soil P levels in 1989 (Fig. 16).

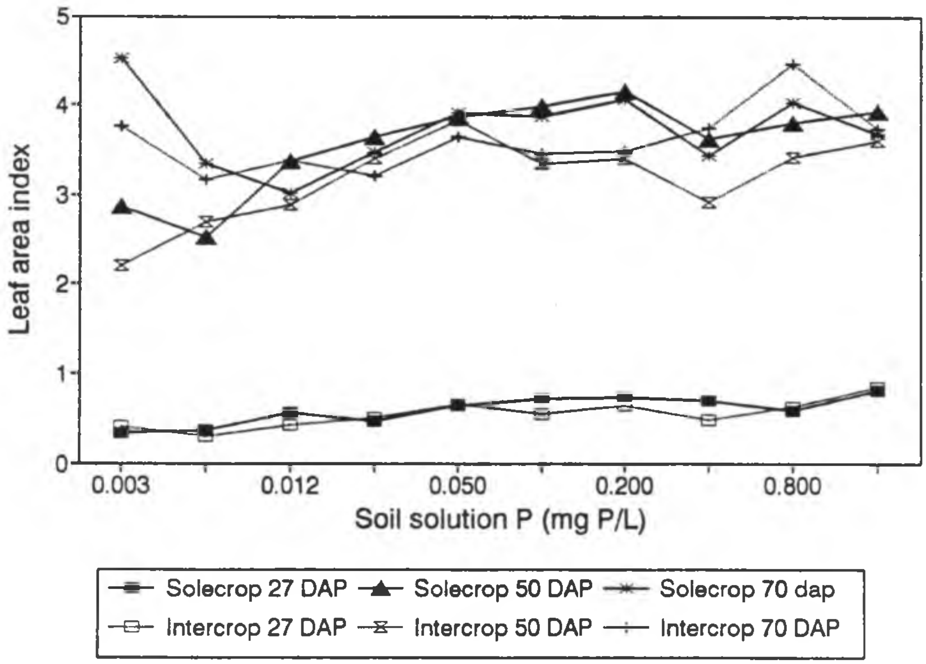

Figure 13. Leaf area index of maize as affected by soil P level and cropping systems at different growth stages at Poamoho during 1989.

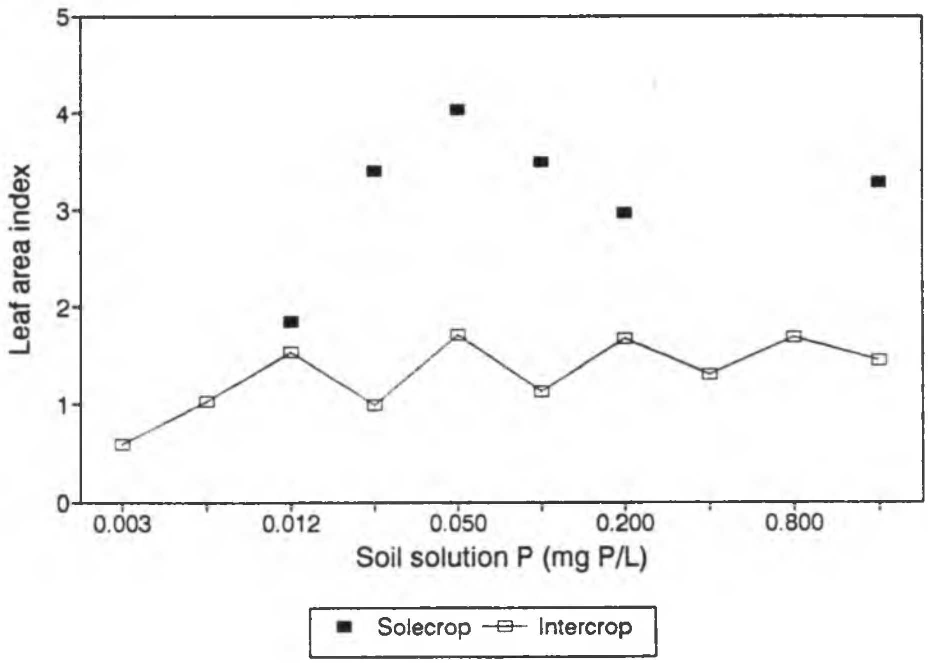

Figure 14. Leaf area index of soybean as affected by soil P level and cropping systems at 77 days after planting at Poamoho during 1988.

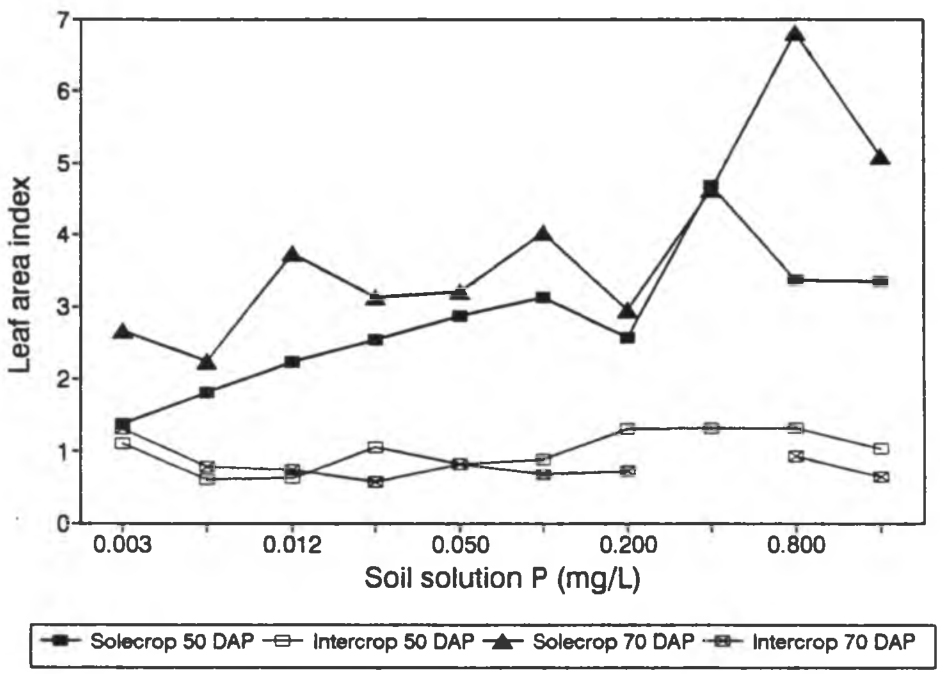

Figure 15. Leaf area index of soybean as affected by soil P level and cropping systems at 50 and 70 days after planting at Poamoho during 1989.

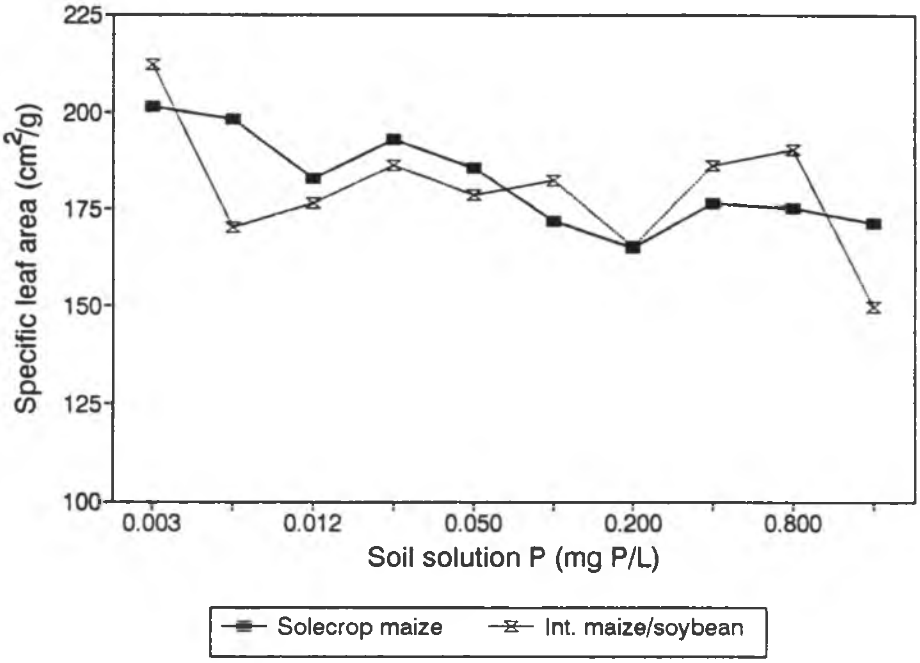

Figure 16. Specific leaf area of maize at different P level at 50 days after planting at Poamoho 1989.

Soybean leaf dry weight was affected by P level, intercropping, days after planting, and their interactions (Appendix 6.1). Intercropping increased SLA of soybean in 1989 but not in 1988 (Appendix 6.3). Soybean SLA was maximum at 50 days after planting in 1988, but in 1989 the intercrop soybean SLA continued to increase until harvest (Table 8). Intercrop soybean SLA was greater than sole crop but remained unaffected by P levels in both the years (Figs. 17a and 17b).

4.4.3 Leaf phosphorus concentration

Environment, soil P, and days after planting were the important factors accounting for the differences in % leaf P concentration of maize and soybean (Appendix 7 and 8).

(i) Maize leaf tissue P concentration

Leaf P increased as soil P increased with a little or no response at higher concentrations. The response to soil P was dependent upon environment, being different not only in the two locations but also in the two seasons. Within environments analysis indicated a quadratic response only at Poamoho 1988. The P concentration in maize leaves sampled 27 days after planting until harvest generally decreased with time (Figs. 18a. 18b, and 18c).

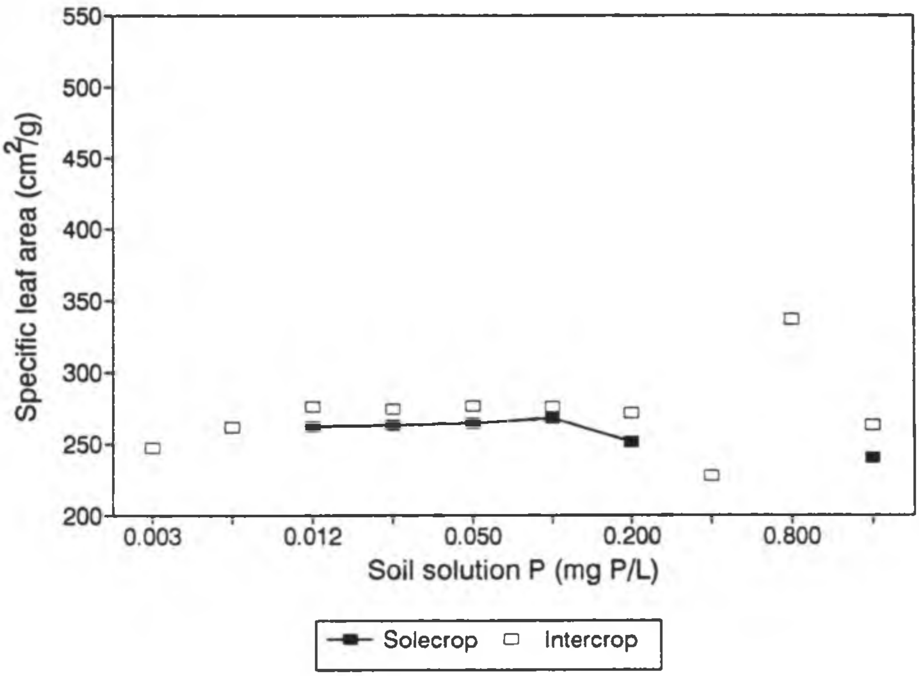

Figure 17a. Specific leaf area of soybean as affected by soil P level and intercropping at 77 days after planting at Poamoho during 1988.

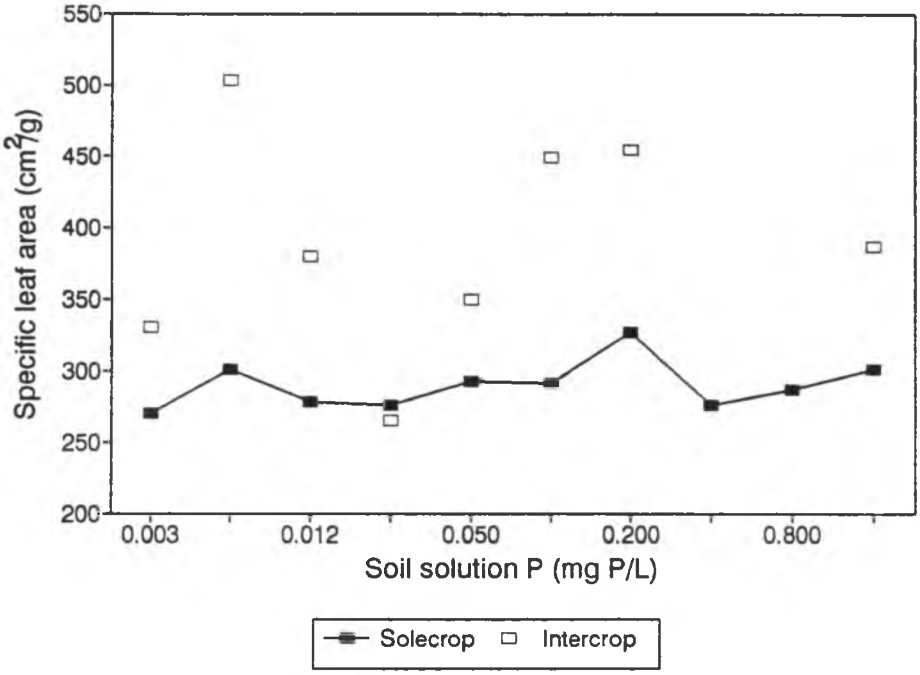

Figure 17b. Specific leaf area of soybean as affected by soil P level and intercropping at 70 days after planting at Poamoho during 1989.

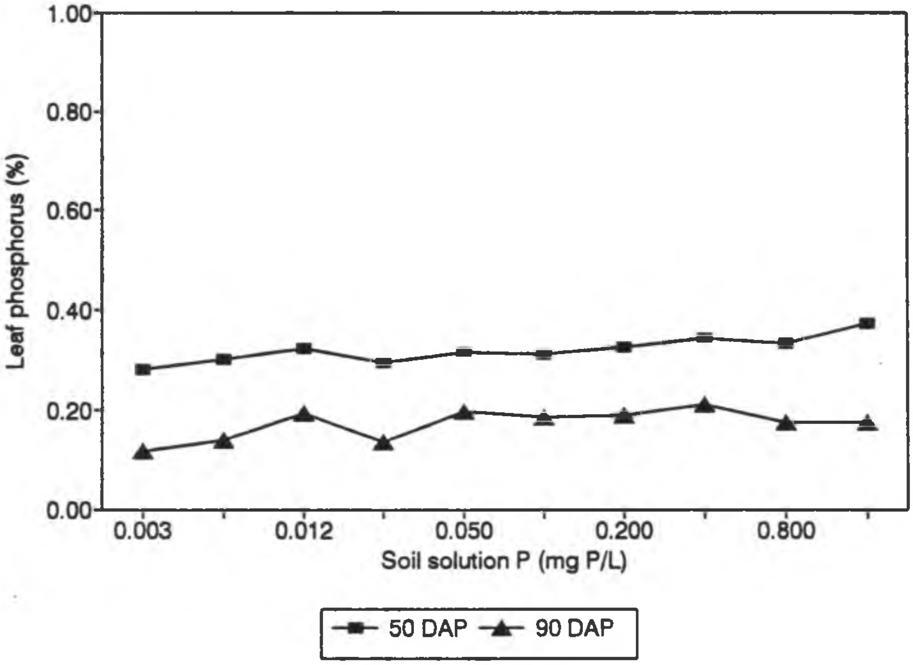

Figure 18a. Maize leaf phosphorus concentration at different P level at Kauai 1987.

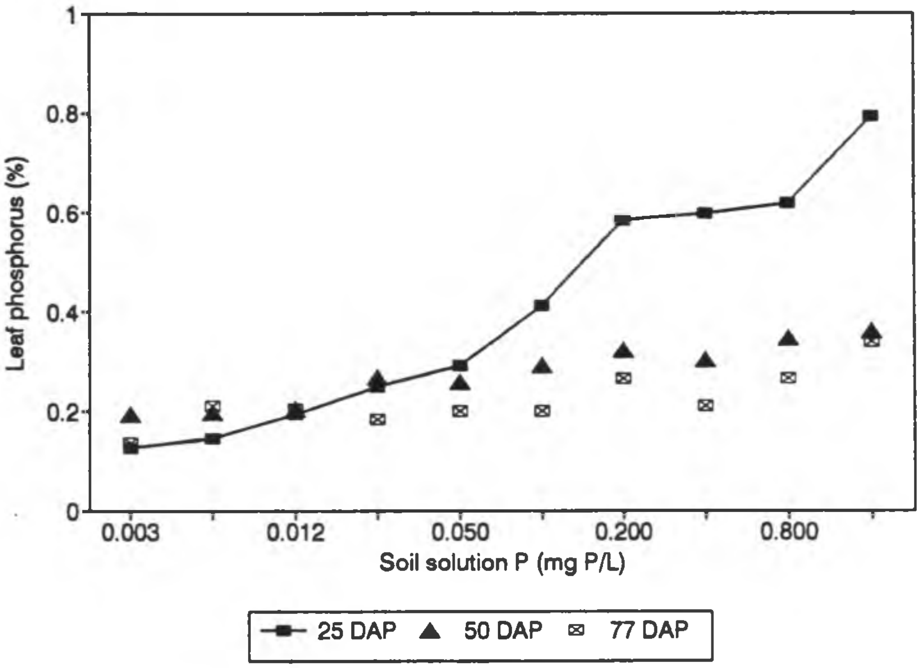

Figure 18b. Maize leaf phosphorus concentration at different P level at Poamoho 1988.

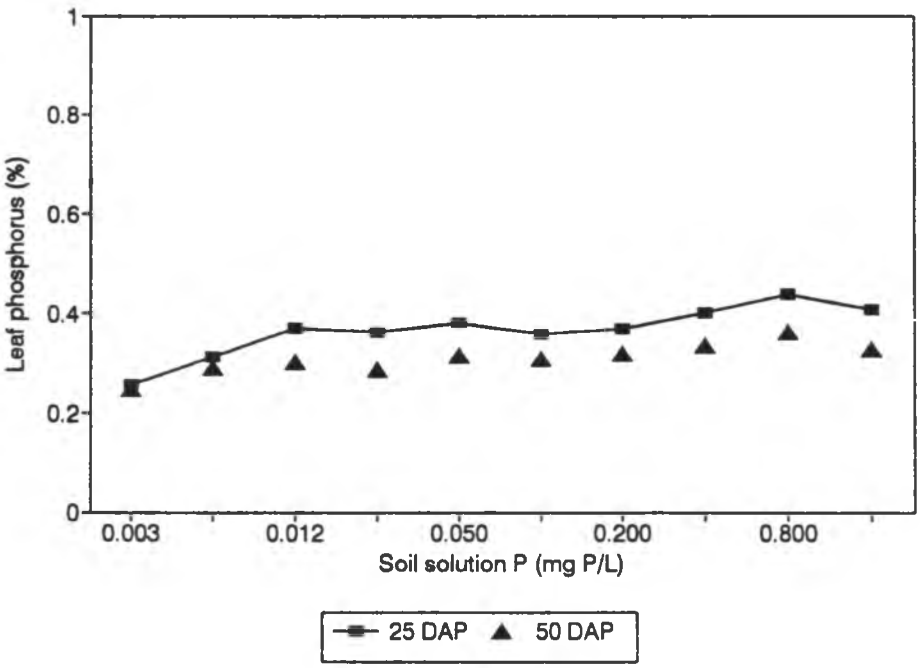

Figure 18c. Maize leaf phosphorus concentration at different P level at Poamoho 1989.

There was no difference in leaf P between sole and intercrop maize. Lack of interactions with system suggested that influence of environments, days after planting and soil P were similar between sole and intercrop maize. However, environment by P levels, environment by days after planting and environments by P levels by date interactions had an effect on leaf P (Appendix 7.1).

(ii) Soybean leaf tissue P concentration

Soybean leaf P concentration generally decreased with increase in plant growth in all environments. Soybean leaf P increased with an increase in soil P with a flat response at higher P levels (Fig. 19a). However, the response was influenced by environment and days after planting (Fig. 19b and 19c). The leaf P of the intercrop soybean was similar to sole crop soybean across environments.

Interpretation of the results of soybean leaf P concentration was complicated by the three factor interactions (Appendix 7.2). Unlike maize, the interactions were more important than the main effects of P level and date in soybean. P concentration of intercrop soybean leaves was sensitive to environments, soil P levels, days after planting, and their interactions. However, the soil P, environment by log(P), and environment by date effects were more influential (Fig 20a and 20b).

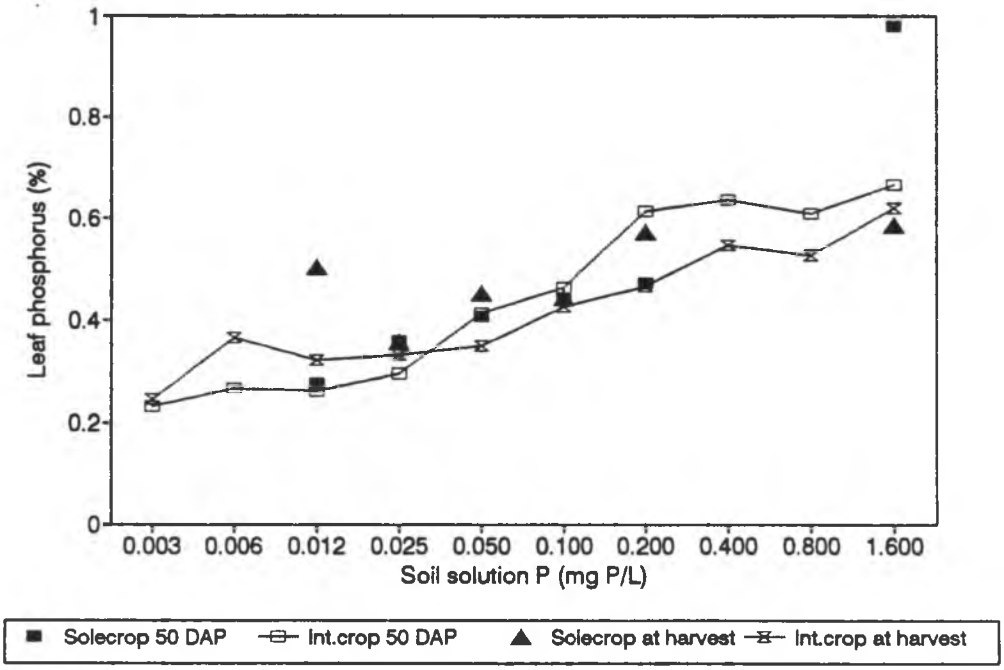

Figure 19a. Soybean leaf phosphorus concentration at different P levels, 27 days after planting at Poamoho during 1988.

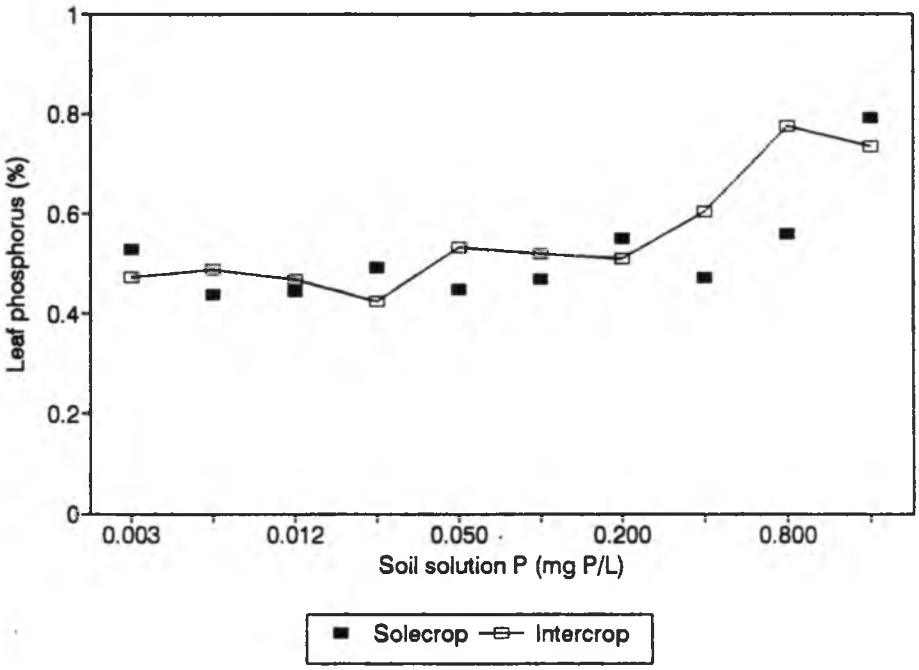

Figure 19b. Soybean leaf phosphorus concentration at different P levels, 27 days after planting at Poamoho during 1989.

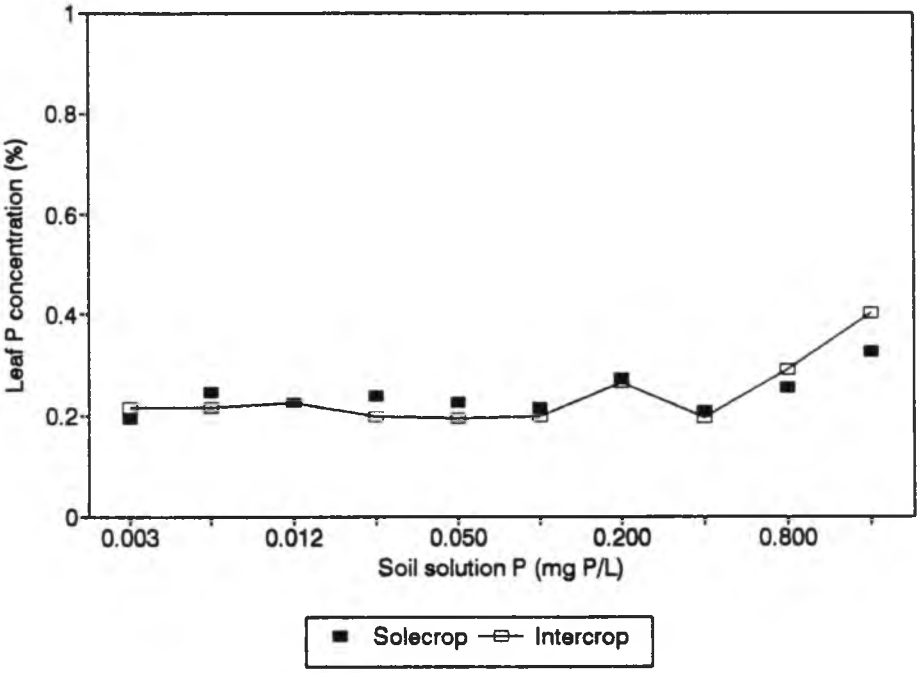

Figure 19c. Soybean leaf phosphorus concentration before harvest at Poamoho 1989.

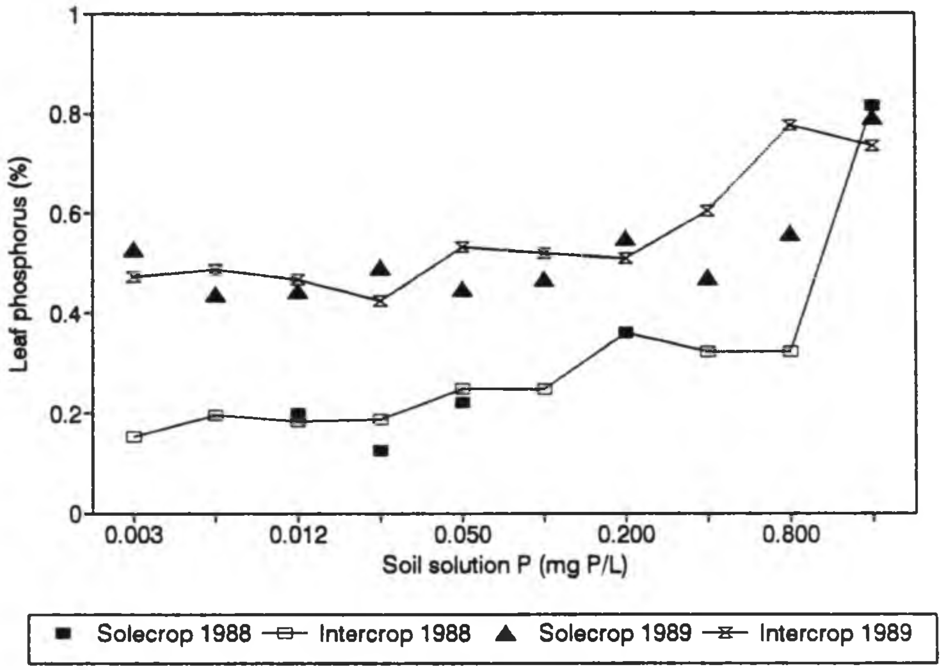

Figure 20a. Soybean leaf phosphorus concentration 27 days after planting at different P level at Poamoho.

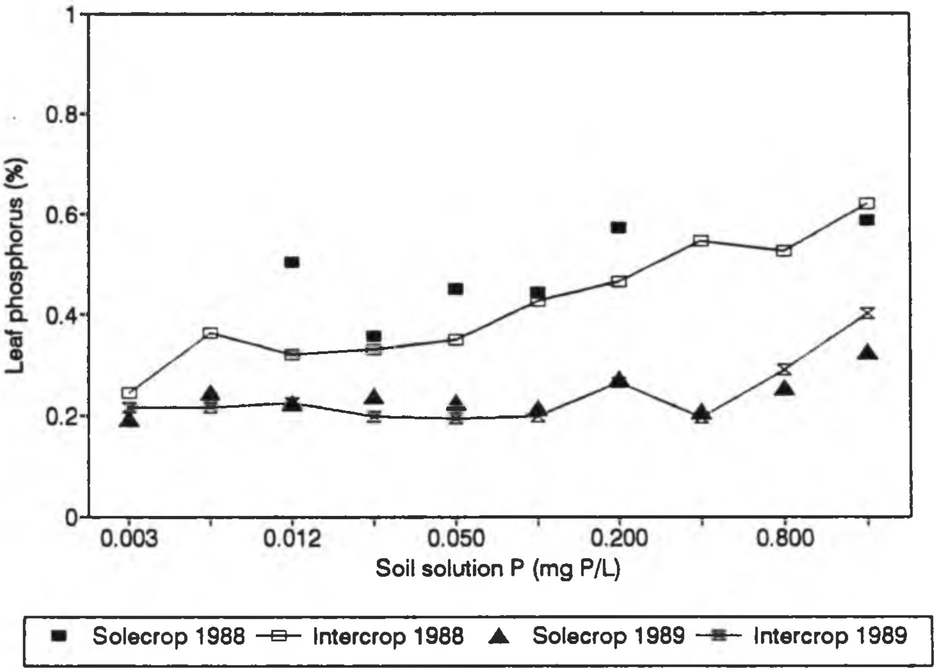

Figure 20b. Soybean leaf phosphorus concentration before harvest at different P level at Poamoho.

4.4.4 Plant and grain P concentration of maize and soybean

Intercropping did not affect the P content of maize grain and stover in all the environments. Environments and soil P level had the large influences on percent plant and grain P content of maize (Appendix 9.2). Grain and total P uptake response to P were different for environments. There was no difference between systems across environments and P levels (Table 9).

Table 9. Effect of intercropping on stover and grain % phosphorus concentration of maize and soybean at Poamoho.

Crop/ system	Poamoho 1988 Stover	Poamoho 1988 Grain	Poamoho 1989 Stover	Poamoho 1989 Grain
Maize	%P		%P	
Sole crop	0.110	0.103	0.123	0.240
Intercrop with/soybean	0.116	0.115	0.105	0.252
Intercrop with/rice	0.122	0.100	-	-
Soybean				
Sole crop	0.268	0.547	0.216	0.488
Intercrop with/maize	0.164	0.438	0.101	0.611

Soybean P uptake, grain and stover P content were mostly affected by intercropping (systems), soil P and environments (Appendix 9.1). The interactions of environment by system, P level by system and environment by soil P by system were important only for P uptake.

4.4.5 Phosphorus uptake and efficiency

Phosphorus uptake by maize increased with the increase in soil P levels, and the response was influenced by the environment (Appendix 9.3b). There was no difference in P uptake of sole and intercrop maize (Appendix 9.3b). For soybean, the P uptake increased with increasing soil P availability and the rate of increase was not same for sole and intercrop soybean. P uptake was not the same for sole and intercrop and was different in the two years at Poamoho (Appendix 9.3a). Table 10 summarizes the results of the regression analysis. Based on significant effects regression models were developed which predicted the P uptake by maize and soybean under sole and intercropping (Table 10).

Table 10. Regression model parameters for predicted P uptake of maize and soybean across P levels, systems and environments. Effects were determined by hypothesis test . Lack of fit was no larger than the appropriate experimental errors except for maize environment by log(P) interaction. ($P<0.05$)

Effects	Regression Coefficients
Maize	
Intercepts	45.60
Environment (E)	25.57
Log(P)	13.78
Log(P)*Log(P)	1.61
Environment*Log(P)	13.64
Environment*Log(P)*Log(P)	3.38
Soybean	
Intercepts	32.24
Environment	-10.61
Log(P)	6.68
Log(P)*Log(P)	0.50
Environment*Log(P)	-1.92
System	-11.32
Log(P)*system	-1.44

Phosphorus uptake was no different in intercrop maize than sole crop maize. But intercrop soybean extracted less P than sole crop soybean. The total P uptake by maize and soybean (taken together) in the maize/soybean intercrop was higher than the sole crops maize (Table 11, 12). Phosphorus uptake increased with the increasing soil P availability in maize and soybean irrespective of system and year (Table 12).

Table 11. Sample means for phosphorus uptake as affected by year, P levels and intercropping at Poamoho.

	Maize		Soybean		
P levels	Sole	Intercrop	Sole	Intercrop	Maize+soybean
(mg/L)			kg/ha)		
Poamoho 1988					
0.003	4.38	3.14	-	6.49	9.63
0.006	-	-	-	6.98	-
0.012	7.42	8.81	19.05	12.12	20.93
0.025	5.15	8.07	19.73	13.40	21.47
0.05	10.78	13.58	42.17	14.15	27.73
0.1	17.25	16.18	15.16	17.71	33.89
0.2	-	5.41	25.93	25.92	31.33
0.4	27.10	18.29	-	20.95	39.24
0.8	-	19.90	-	31.30	51.20
1.6	-	15.81	66.06	39.36	55.27
Mean	12.01	11.91	31.35	16.81	29.30
Poamoho 1989					
0.003	-	-	10.11	5.86	-
0.006	26.05	30.81	14.90	5.58	36.39
0.012	24.29	24.56	16.16	4.28	28.84
0.025	26.96	30.75	16.26	4.21	34.96
0.05	28.01	25.91	23.35	4.54	30.45
0.1	29.43	32.82	24.43	3.77	36.59
0.2	58.18	45.12	28.99	7.28	52.40
0.4	35.88	46.84	18.13	8.13	54.97
0.8	44.56	49.20	29.87	8.92	58.12
1.6	113.00	-	38.16	8.15	-
Mean	35.52	32.13	21.45	5.24	37.16

Table 12. P uptake of maize and soybean across P levels for different systems as predicted by regression analysis (Appendix 9). The parameters in the regression models were based on real effects determined by analysis of variance ($P<0.05$). (LER_p was calculated based on predicted P uptake assuming $PLER_p$ of maize=1).

	Soybean		Maize		
P levels	Sole	Intercrop		Maize+Soybean	LER_p
(mg/L)	(kg/ha)				
Poamoho 1988					
0.003	32.0	16.6	8.4	25.0	1.52
0.006	34.3	18.1	11.0	29.0	1.53
0.012	36.7	19.6	13.2	32.8	1.53
0.025	39.4	21.3	15.3	36.6	1.54
0.05	41.9	23.0	16.9	39.9	1.55
0.1	44.6	24.9	18.1	43.0	1.56
0.2	47.4	26.8	19.1	45.8	1.56
0.4	50.3	28.8	19.7	48.5	1.57
0.8	53.2	30.8	20.0	50.8	1.58
1.6	56.2	33.0	20.0	53.0	1.59
Mean	43.6	24.3	16.2	40.4	1.56
Poamoho 1989					
0.003	20.5	5.1	33.8	38.8	1.25
0.006	21.6	5.4	34.9	40.2	1.25
0.012	22.9	5.7	36.9	42.7	1.25
0.025	24.3	6.3	40.0	46.3	1.26
0.05	25.7	6.8	43.9	50.8	1.27
0.1	27.2	7.5	48.7	56.2	1.27
0.2	28.9	8.2	54.4	62.7	1.28
0.4	30.6	9.1	61.0	70.1	1.30
0.8	32.3	10.0	68.6	78.5	1.31
1.6	34.2	11.0	77.0	88.0	1.32
Mean	26.8	7.5	49.9	57.4	1.28

LER based on P uptake, which measured performance and efficiency of land use by intercropping in extracting P from the soil, was higher than unity at each P level in 1988 and in 1989 (Table 12). On an average intercropping system (maize plus soybean) extracted 56% more P in 1988 and 28% more in 1989 compared to sole cropping. In other word 28 to 56% more land area under sole cropping would be required to extract same amount of P as in intercropping. LER value appeared to increase with increasing soil P. Although, the difference of LER, based on P uptake, was only 7 percent between lowest and highest P level.

Phosphorus use efficiency, as measured by amount of grain or dry matter produced per unit of P uptake, for maize and soybean decreased with increases in soil P regardless of cropping system in 1988 and in 1989 (Table 13). Phosphorus use efficiency (grain yield or dry matter/P uptake) of intercrops (maize plus soybean) was greater than soybean but was less than maize. Greater reduction of P use efficiency in intercrop soybean was observed than in intercrop maize relative to their sole crops. P use efficiency was reduced by intercropping in both year.

Table 13a. P use efficiency based on grain yield across P level for different systems at two years at Poamoho. Predicted P uptake and grain yield from the regression analysis (Appendix 9) were used for the calculation of P use efficiency. The parameters in the regression models were based on real effects determined by analysis of variance (P<0.05).

	Soybean		Maize		
P levels	Sole	Intercrop	Sole	Intercrop	Maize+soybean
(mg/L)	--------(kg grain yield/kg P uptake)--------				
Poamoho 1988					
0.003	67.9	59.4	333.3	298.9	139.9
0.006	65.7	54.5	262.6	236.2	123.2
0.012	63.6	50.0	224.0	202.1	111.3
0.025	61.5	45.8	199.8	180.8	102.1
0.05	59.6	42.3	185.7	168.5	95.6
0.1	57.8	39.0	177.2	161.2	90.5
0.2	56.1	36.2	172.6	157.4	86.6
0.4	54.5	33.5	171.2	156.5	83.5
0.8	53.0	31.2	172.6	158.1	81.1
1.6	51.6	29.0	176.7	162.2	79.3
Mean	59.1	42.1	207.6	188.2	99.3
Poamoho 1989					
0.003	160.3	85.3	229.7	221.1	203.4
0.006	155.5	80.0	224.6	216.3	198.1
0.012	150.5	74.2	214.4	206.6	188.7
0.025	145.2	67.7	199.8	192.5	175.7
0.05	140.3	61.6	183.9	177.3	161.8
0.1	135.4	55.8	167.4	161.5	147.4
0.2	130.6	50.3	151.4	146.1	133.5
0.4	126.0	45.3	136.3	131.6	120.4
0.8	121.5	40.8	122.6	118.3	108.5
1.6	117.1	36.7	110.2	106.4	97.7
Mean	138.2	59.8	174.0	167.8	153.5

Table 13b. P use efficiency based on total plant dry matter across P level for different systems at two years at Poamoho. Predicted P uptake and dry matter by the regression models were used for the calculation of P use efficiency. The parameters in the regression models were based on real effects determined by analysis of variance (P<0.05).

	Soybean		Maize		
P levels	Sole	Intercrop	Sole	Intercrop	Maize+Soybean
(mg/L)	--------(kg dry matter/kg P uptake)----------				
Poamoho 1988					
0.003	246.0	197.8	1336.2	1169.3	524.4
0.006	234.8	182.8	1047.1	919.3	461.3
0.012	224.6	169.2	888.7	782.7	416.5
0.025	214.5	156.3	788.4	696.5	381.7
0.05	205.8	145.3	729.5	646.2	356.9
0.1	197.6	135.4	692.8	615.3	337.7
0.2	190.0	126.3	672.0	598.4	322.7
0.4	182.9	118.1	663.8	592.6	311.0
0.8	176.3	110.7	666.7	596.5	301.8
1.6	170.1	103.9	680.2	610.0	294.7
Mean	204.3	144.6	816.5	722.7	370.9
Poamoho 1989					
0.003	302.2	172.5	733.2	691.6	623.8
0.006	294.7	166.1	717.0	676.7	608.6
0.012	286.8	157.9	684.6	646.5	580.7
0.025	278.2	147.9	637.8	602.8	541.4
0.05	270.0	138.0	587.2	555.3	499.2
0.1	261.8	128.0	534.7	506.0	455.7
0.2	253.7	118.3	483.5	457.7	413.2
0.4	245.7	109.2	435.4	412.5	373.3
0.8	237.9	100.6	391.5	371.1	336.7
1.6	230.3	92.8	352.1	333.9	303.7
Mean	266.1	133.1	555.7	525.4	473.6

4.5 DISCUSSION

Replacement series experiments with varying nutrient levels have compared periodic dry matter and nutrient uptake of sole crop maize with intercrop components (Dalal 1974, Chang and Shibles 1985). Taken together, the intercrop components often produced more dry matter and extracted more nutrients than the sole crops, although the individual components produced less. It is not known whether such a response prevails at the same population density of main crop in sole and intercropping under a gradient of nutrient availability in different environments. In replacement series, due to the difference in the population density of sole crops and the intercrop components, the comparison of sole and intercrop components included the effect of reduced density and interference by the other component. In my study with the maize population density being the same in the sole crop and intercrops, dry matter production and nutrient uptake by intercrop maize demonstrated the influence of the addition of the soybean crop. The intercrop soybean had a small effect on the productivity of intercrop maize across P levels but the component maize greatly affected intercrop soybean. The dry matter yield reduction of soybean due to intercropping was greatest in the higher soil P levels and in the high productivity environment of Poamoho 1989. The effect P, however, at the higher P level at Poamoho 1989, was confounded with the effect of reduced light to intercrop soybean because of shading by taller and more vigorous maize. At Poamoho 1988, however, the effect of maize on intercrop soybean was less severe because of the reduced growth of maize caused by factors other than soil P availability.

Specific leaf area is dependent upon the environments in which leaves develop. Plant growth and development is influenced by crop structure and shading by the leaves of the same as well as other species within the crop canopy. In intercrop systems the canopy environment was strongly influenced by the maize growth, which affected the leaf properties of soybean. Greater specific leaf area (leaf area per unit of leaf dry weight) of intercrop soybean compared to sole crop soybean was observed reflecting the shading effect of maize, but the maize canopy was unaffected by soybean growth. Thus leaf properties of intercrop maize remained unchanged from those in sole crop.

Leaf P concentration was unaffected by the influence of a companion crop for both maize and soybean. This is probably due to fact that the effect of competition for soil P may not be reflected in leaf P concentration. Because of the small zone of depletion, competition for P is expected only when the roots of the companion crops intermingle. The differences in leaf P concentration in sole and intercrop at different growth stages was not associated with interspecific competition. Differences due to environmental factors, nutrient flux, and sink/source relationships were sufficiently large enough to mask any difference between sole and intercrops.

Phosphorus use efficiency, as measured by the amount of grain yield or dry matter produced per unit P uptake, is the function of grain and stover yield and P concentration in grain and stover. The efficiency of P extraction, reflected by the same leaf, stover and grain P concentration and P uptake by sole and intercrop maize was not effected by intercropping. The efficiency with which P is utilized to produce yield was reduced by intercropping but P uptake showed no difference by sole and intercrop maize. However, the efficiency of P use decreased with increases in P availability in maize and soybean. The decrease in efficiency was correlated with increase in P uptake irrespective of system. P uptake by intercrops taken together was greater than sole maize in both years at Poamoho. Whereas, P uptake by sole crop soybean was more than intercrops only in 1988 but not in 1989. The P use efficiencies of intercrops (maize plus soybean) were lower than maize but higher than soybean.

The whole idea of intercropping systems being more sustainable is questionable. The intercrop systems are relatively more productive under a wide range of P availability and environmental conditions. The system is more productive but it also extracts more resources, such as phosphorus, from the soil. At higher P levels demand, as well as P uptake, increased with the increase in the availability. Thus, interspecific competition may be severe. In soybean, the inter- and intraspecific competition was further affected by population density difference in sole and intercrop, effect of light, and three-factor interactions (environment by P level by system). At lower P levels, because of higher P use efficiency, there could be greater degree of niche differentiation resulting in relatively more extraction of soil P in relation to availability. If this is true, intercropping systems very commonly practiced in low productivity environments in so called low-input sustainable agriculture, will be less sustainable.

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5.

EFFECT OF SOIL PHOSPHORUS ON ROOT DRY MATTER AND DISTRIBUTION IN INTERCROPPING SYSTEMS

5.1 SUMMARY

Root research in intercropping is not as common as studies on the above ground canopy. Information on root interaction in response to soil P availability is lacking. Information on roots was therefore collected from intercropping experiments conducted over two years at the University of Hawaii Poamoho Experiment Station. The objectives were to measure the effects of P and intercropping system on root dry matter and root length. Root length of subsamples was physically measured and also estimated by the modified Tennant's intersection method.

Total root dry matter was affected by intercropping system in 1988, whereas soil solution P concentration had no effect on total root dry matter per unit of soil volume. In general, intercropping produced more roots at the surface, which differed between the years.

The interaction of P level with system in the surface layer indicated increased root biomass in the maize/soybean intercrop mixture. An estimate of LER based on root dry weight (estimated with the assumption of same proportion of above-ground dry matter of components in the intercrop mixture) was within the range of those based on above ground dry matter and grain yield.

5.2 INTRODUCTION

Intercropping can lead to improved use of resources, particularly light, water, and nutrients (Willey 1979, Gregory and Reddy 1982, Marshall and Willey 1983, Trenbath 1986). The possible mechanisms of improved use of resources may be hypothesized as due to niche separation (roots of different species occupy different space avoiding each other), increased root density, and proliferation of roots in intercropping, which results in a greater volume of soil being explored. If two crops grown together demonstrate an intercropping yield advantage, it is likely that they do so because their niches do not overlap sufficiently (Vandermeer 1990). At the process level, the advantage of intercropping depends on the extent to which the components are not in competition (Jensen 1978, Willey and Reddy 1981).

Because the competitive relationships between species change with nutrient availability (Chapter 3), intercrop performance may be affected by the differential response of intercrop component root biomass production and distribution in relation to P availability. Wilson (1988), in a comprehensive review indicated intense positive root interaction between components of intercrops. The higher yields of mixtures tended to occur in experiments that allowed different species to root at different depths, which is interpreted as niche separation. It is generally assumed that competition will be reduced when environmental resources are added and may even cease if the available supply is more than the combined demands of both crops. However, he found little evidence in published reports that adding resources reduces competitive effects, but the competitive balance between species was often shifted at higher resource levels. However, the competition for nutrients or lack of it is confounded with competition for light and moisture such that the outcome of competition represents an overall response. Willey and Reddy (1981) concluded that the main determinant of yield advantage of intercropping was the above ground interaction between the canopies. Below ground root interactions were important in determining the competitive balance of the two crops.

Information on how roots in intercropping systems are influenced by P availability is lacking. An experiment was therefore conducted to test the hypothesis that niche separation of roots in intercropping is not influenced by levels of P in the soil solution. Since diffusion is the dominant process of P movement in soil, P uptake in intercrops is most influenced by root proliferation and the soil volume accessible to roots. It has been hypothesized that roots in intercropping are exposed to greater soil volume (due to niche separation) resulting in more uptake of nutrients which result in an advantage over sole crops.

The objectives of the present study were:

To quantify the effect of soil phosphorus on root dry matter, root length density and distribution in intercropping systems compared to sole crops.

To quantify root interaction in intercropping systems as related to phosphorus availability.

5.3 MATERIALS AND METHODS

5.3.1 Location of experiment, site and soil description

Soil core samples were taken from two field trials conducted during the summers of 1988 and 1989 at the University of Hawaii Poamoho Experiment Station on a silty clay of the Wahiawa series classified as clayey, kaolinitic, isohyperthermic, Rhodic Eutrustox.

5.3.2 Treatments and experimental design

Established plots were utilized for the intercropping trials where ten phosphorus concentrations in soil solution have been maintained since 1971. The target concentrations were determined using phosphorus sorption techniques (Fox and Kamprath 1970). Main plots of ten target P levels (0.003, 0.006, 0.012, 0.025, 0.05, 0.1, 0.2, 0.4, 0.8 and 1.6 mg P/L in soil solution) were laid out in an augmented block design (Federer 1956). Four P levels, 0.012, 0.025, 0.05 and 0.1 mg P/L, were replicated three times, and the rest of the unreplicated treatments constituted the remainder of the 18 main plots (15.24 m by 5.49 m). In

1988, each main plot contained either maize, soybean, or rice sole crop and two intercrop systems (maize/soybean and maize/rice). In 1989, main plots contained the maize/soybean intercrop with both maize and soybean as sole crop checks.

Maize spacing was 0.90 m by 0.25 m for both sole crop and intercrop. Sole crop soybean was spaced 0.45 m by 0.10 m apart. One row of soybean, spaced 0.90 m by 0.10 m, was planted between two rows of maize in the maize/soybean intercrop. Sole crop rice was planted at a row spacing of 0.30 m at a seeding rate of 100 kg/ha. Two rows of rice were planted between two rows of maize in the maize/rice intercrop.

Appropriate amounts of P fertilizer were applied to each treatment as triple superphosphate before the last tillage operation to achieve the target levels of P in the soil solution. Nitrogen as urea and potassium as potassium chloride were supplied at the rate of 150 kg/ha each before planting. Soybean was inoculated with rhizobium. In 1989, because of bird damage to seedlings, soybean was replanted four days after the emergence of maize. A drip irrigation system was set up for uniform water supply. Experimental plots were maintained weed free by weeding at 30 and 75 days after planting in 1988. In 1989, weed control was accomplished with preemergence application of alachlor (Lasso) herbicide followed by a post emergence spray of bentazon (Basagran). There was a slight phytotoxic effect of Basagran herbicide on soybean which appeared to recover completely by midseason.

5.3.3 Sampling and root recovery procedure

Soil samples for root recovery were taken just before physiological maturity of maize at depths of 0 to 0.15 m and 0.15 to 0.40 m. In 1988, three samples were taken from each subplot within each P main plot using a soil bucket auger (7.6 cm diameter). In 1989 only four levels of P (0.003, 0.012, 0.1 and 1.6 mg P/L) were sampled. A total of 324 and 72 soil core samples were collected in 1988 and 1989, respectively. Sample sites were selected midway between two rows of maize and soybean in sole crop within the harvest area. In intercrop soybean the samples were taken between alternating maize and soybean rows. The weight of each soil sample was recorded and moisture content determined. Volume of the soil sample was calculated based on the bulk density of the soil (g cm^{-3}) and dry weight of the soil sample.

Roots were washed using Gillison's Hydropneumatic Elutriation System (Smucker et al 1982). Soil samples of approximately 200 cm^3 were placed in each of the root washing chambers. After each soil sample was washed, three components were recovered: (a) washed sample including biological debris collected on the primary sieve (b) some larger clean roots left in the washing chamber and (c) very fine roots (rinse) washed through the primary sieve and collected using a very fine sieve which also contained debris. The sample components were again separated into sample roots and leftover debris by floating in a saline solution (approx. 1 N). The separated sample contained some debris and also the leftover debris component contained some roots. Roots in the sample components, leftover debris and rinse (roots recovered from the washing chamber were devoid of any debris) were very carefully separated by hand into clean roots and debris using forceps. A visual estimate of % roots was made when it became impossible to separate very fine roots from the debris. The quantity of dry roots in each sample, adjusted for debris after cleaning and separation was calculated as root dry weight per 100 cm^3 of soil (10^{-2} mg cm^{-3}). Actual root length of dried roots was measured for subsamples using a ruler. On the same subsample, root length was also estimated by the modified Tennant intersection method (Tennant 1981). A linear relation of root dry weight to root length based on subsamples was used for calculating root length for all samples.

5.3.4 Statistical analysis

Root weight and length per unit volume of soil were utilized for statistical analysis. Observations were adjusted to remove block effects, which were calculated using the replicated treatments. An analysis of variance was performed for (a) total root dry weight, R_{total} (b) root weight at 0 to 0.15 m depth, $R_{surface}$ (c) root weight at 0.15 to 0.40 m depth, $R_{subsurface}$ (d) total root length density (e) root length density at 0 to 0.15 m depth (f) root length density at 0.15 to 0.40 m depth and (g) ratio of surface root weight to subsurface root weight. Total root dry weight (10^{-2} mg cm^{-3}) was calculated as mean root dry weight in 0 to 0.15 m surface layer and 0.15 to 0.40 m subsurface layer (i.e. $(0.15\ R_{surface} + 0.25\ R_{subsurface})/40$). Root length in each layer was calculated using the linear relation of root dry weight to root length. Root length density was calculated as the total root length per unit soil volume. Analysis of variance was performed for each year separately, using the SAS General Linear Model (GLM) procedure (SAS Institute Inc. 1986). Soil phosphorus levels were log transformed for regression analysis.

LER, an index for assessing intercrop performance, was calculated based on root dry weight assuming the same proportion of component roots as in the above-ground shoot dry matter. Willey and Reddy (1979) had used a similar approach. The calculation of LER, based on actual root dry weight of each intercrop component, was not possible because of the problems in separating roots of different species from the mixture.

5.4 RESULTS

5.4.1 Root recovery and estimates

The root recovery estimate of 11 soil core samples indicated that 7.6% of the roots were lost through the primary sieve. Only 69.3% of the roots were recovered on average from the separated sample (Table 14).

The regression of root length on root dry weight was linear in both years (Figs. 21 and 22). The root length estimates from the Tennant method followed closely the actual measurements (Fig 23).

Table 14. Percent root content recovered after processing roots using Gillison's Hydropneumatic Elutriation system for eleven soil core samples after separation in saline solution.

Sample Number	Percent root recovered from Sample	Washing chamber	Debris	Rinse
1	61.73	19.04	7.31	11.92
2	71.05	19.38	5.02	4.54
3	65.90	19.54	14.56	-
4	77.91	13.49	7.36	1.23
5	67.89	0.00	19.27	12.84
6	68.28	2.76	22.07	6.90
7	50.49	24.10	13.68	11.73
8	67.36	15.28	4.86	12.50
9	71.46	2.97	13.01	12.56
10	83.92	1.46	9.94	4.68
11	76.24	10.64	8.91	4.21
Mean	69.29	11.69	11.45	7.55

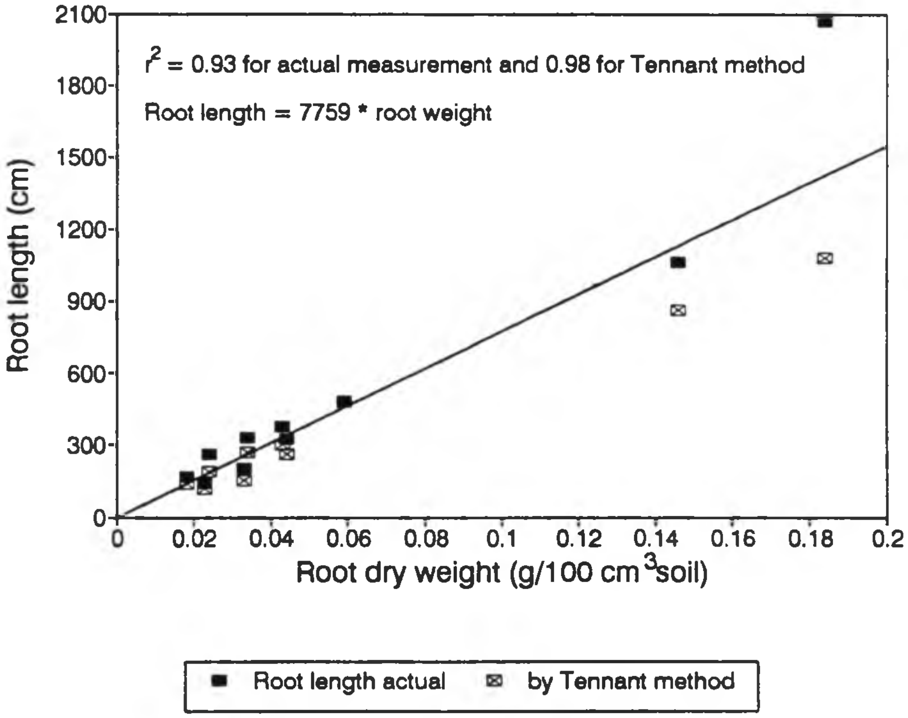

Figure 21. Linear regression of root length against root dry weight at Poamoho 1988.

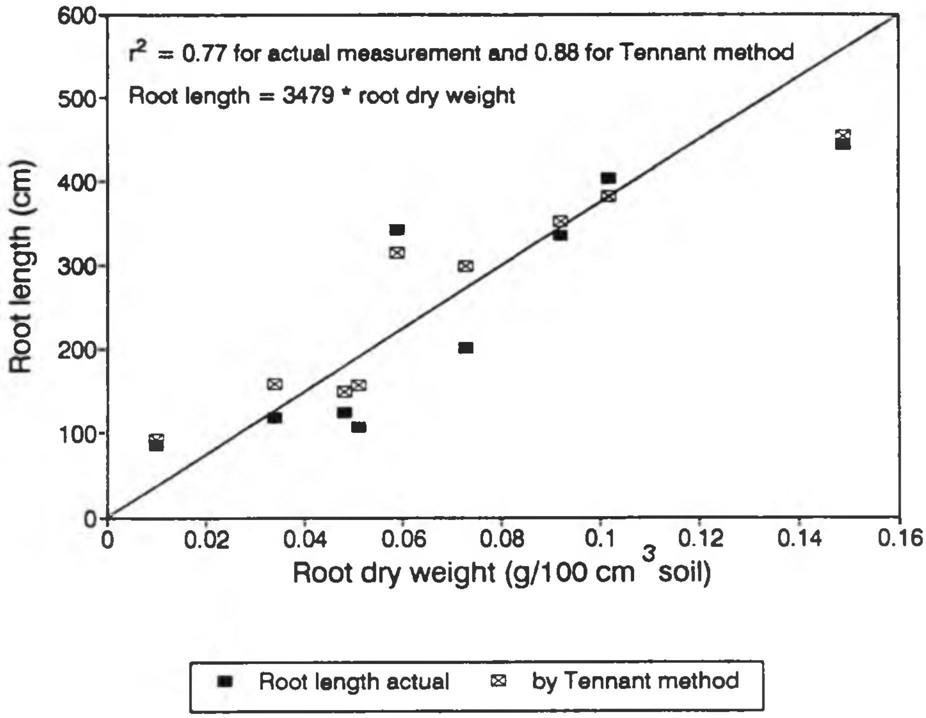

Figure 22. Linear regression of root length against root dry weight at Poamoho 1989.

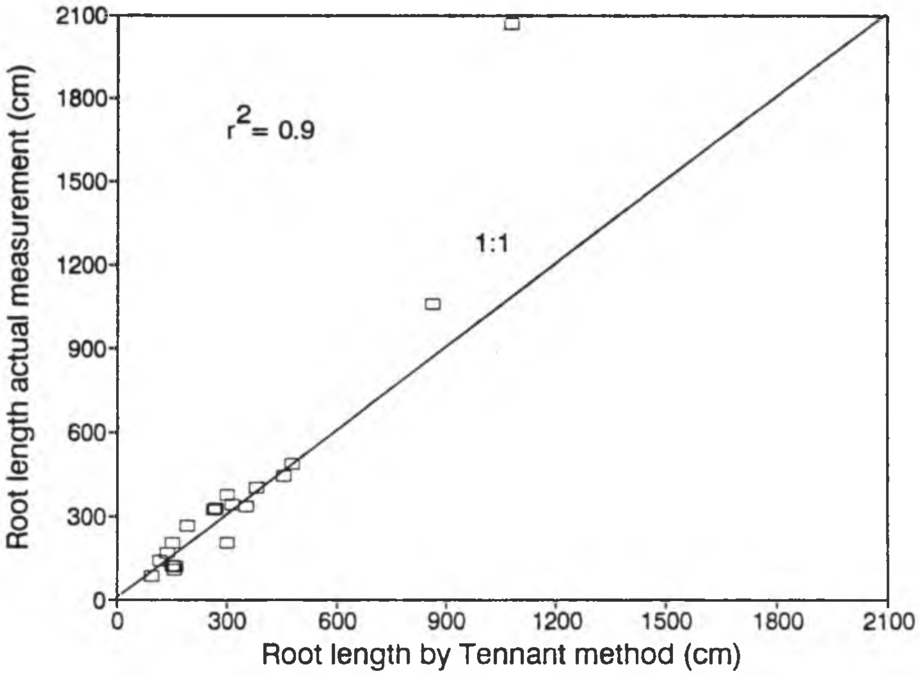

Figure 23. Actual root length measurement versus Tennant method.

5.4.2 Main effect of soil P and intercropping

Soil P level had no effect on increasing root dry weight per unit of soil core volume (Appendix 10). This result was consistent in the surface as well as the subsurface depth in both years. This does not indicate the total root biomass response to P as such, rather it reflects the density of roots in the soil volume in the specific layers. The root growth at two depths was independent of P concentration in the soil solution.

There was no difference in root dry weight per unit of soil volume between sole crop maize and maize/soybean intercrop for the surface layer 0-0.15 m as well as in the 0-0.40 m layer (Table 15). However the maize/soybean intercrop produced more root dry weight than sole crop soybean in both 0-0.15 m and 0-0.40 m layers but the maize/rice intercrop system produced the same root dry weight as sole crop rice. There was no difference in root dry weight between intercrop mixtures and either of the sole crops in the subsurface layer in 1988. In 1989, no differences were observed between sole crops and the maize/soybean intercrop for each layer (i.e., 0-0.15, 0.15-0.40 and 0-0.4 m). Since root length variables were derived by the weight/length relationship, the response pattern of root length density was exactly the same as that of the root dry weight (Table 15).

Table 15. Effect of cropping systems on mean root dry weight, root length density, and root dry weight ratio (ratio of root dry weight at 0 to 0.15 m surface to 0.15 to 0.40 m subsurface layer) across P levels at Poamoho.

	Soil layers						
	Root dry weight			Root length density			Root wt. ratio
Variables	0-0.15m	0.15-0.4m	0-0.4m	0-0.15m	0.15-0.4m	0-0.4m	0-0.15/0.15-0.4
		(10^{-1} x g m^{-3})			(100 x cm^{-2})		
Poamoho 1988							
Maize	62 (5)	33 (3)	44 (3)	551 (45)	292 (28)	389 (26)	1.96 (0.2)
Soybean	40 (4)	29 (6)	33 (5)	255 (38)	255 (50)	292 (41)	1.59 (0.2)
Rice	47 (8)	25 (3)	33 (4)	417 (70)	219 (24)	293 (37)	1.92 (0.2)
Maize/soyb	67 (2)	34 (3)	46 (2)	594 (22)	299 (25)	410 (19)	2.22 (0.2)
Maize/rice	53 (2)	28 (2)	37 (2)	469 (18)	247 (16)	330 (15)	2.02 (0.2)
C.V. (%)	14.4	37.8	21.6	14.4	37.8	21.5	35.0
Poamoho 1989							
Maize	43 (5)	25 (5)	32 (4)	181 (20)	106 (21)	134 (16)	2.52 (0.5)
Soybean	48 (5)	32 (5)	38 (3)	203 (22)	135 (21)	161 (13)	2.01 (0.4)
Maize/soyb	56 (8)	26 (5)	37 (5)	238 (35)	108 (19)	156 (20)	2.90 (0.5)
C.V. (%)	38.0	52.0	35.8	38.0	52.0	35.8	60.5

Numbers in parenthesis are standard errors of means.

5.4.3 Surface root interaction

The interaction of log(P) by system interaction indicated that the response to P was different for different systems for the surface (0 to 0.15 m) root dry weight (Appendix 9, Figs. 24 and 25). The nature of the interaction was not clear. Analysis of the root dry weight ratio (RWR) between two layers indicated no difference due to intercropping, lack of P response and interaction between P level and system.

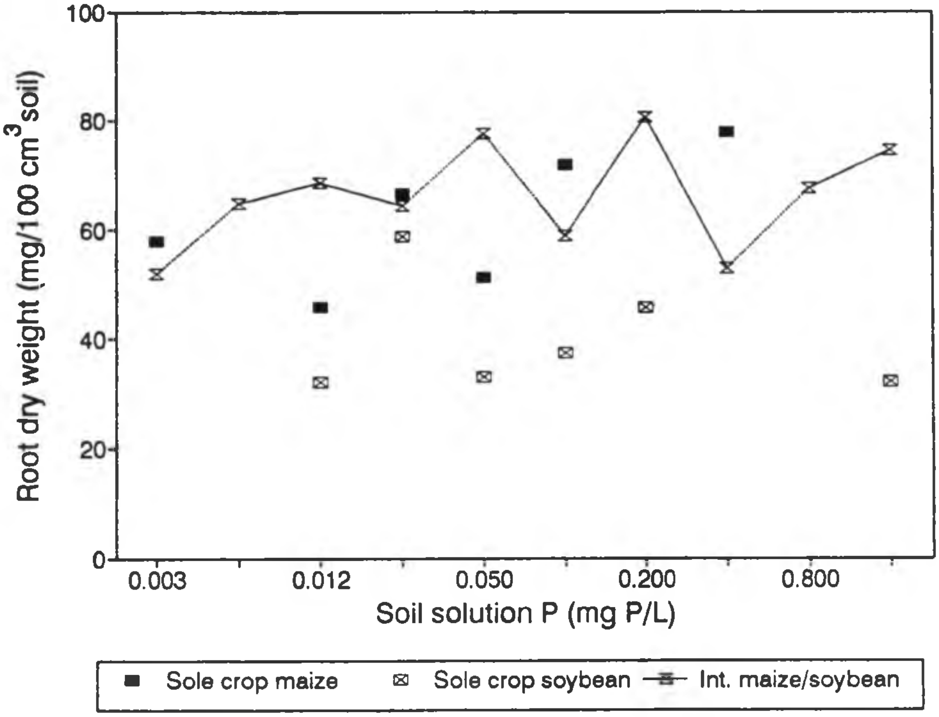

Figure 24. Surface root dry weight (0 to 0.15 m) as influenced by intercropping and soil P levels at Poamoho 1988.

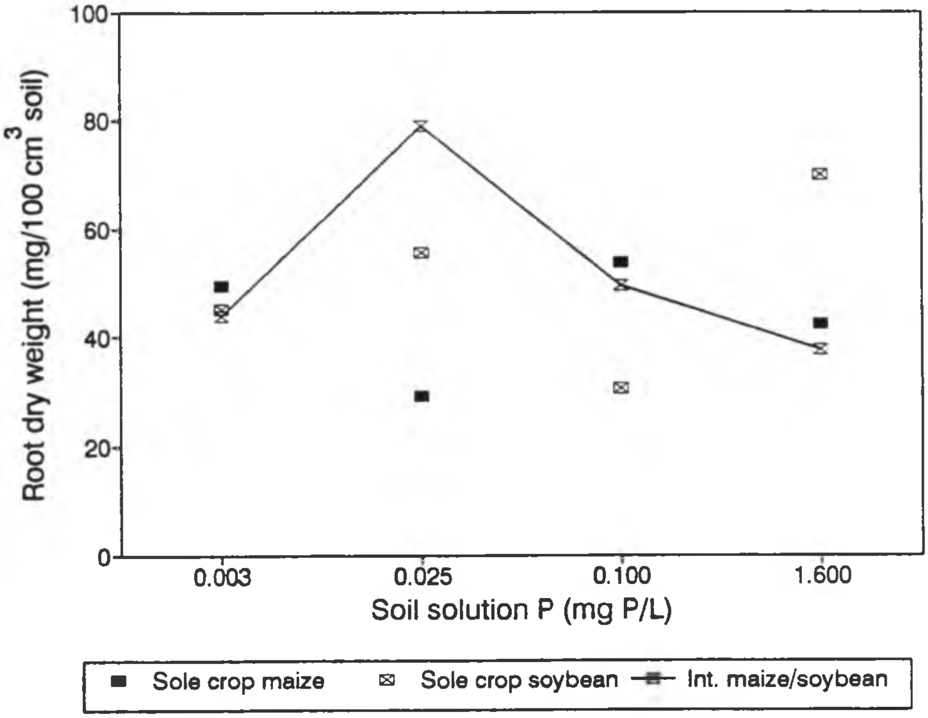

Figure 25. Surface root dry weight (0 to 0.15 m) as influenced by intercropping and soil P levels at Poamoho 1989.

5.4.4 LER based on root dry weight

The proportion of maize and soybean roots in the intercrop were calculated using the above ground dry matter proportions of component crops. By this method the LER estimates, using the 0-0.15 m surface root dry weight, were 1.28 in 1988 and 1.10 in 1989. Based on mean root dry weight (0-0.40 m), the estimated LER of 1.17 in 1988 and 1.05 in 1989 were within the range calculated based on dry matter and grain yield (see chapter III).

5.5 DISCUSSION

The root samples that were processed using Gillison's Hydropneumatic Elutriation system contained clean roots, biological debris and heavier soil or sand aggregates. From this it was difficult to estimate total roots excluding all other material from the samples. By careful retrieval of roots from the samples, satisfactory estimates of the total amount of roots were obtained. Root loss in the recovery process was negligible.

In both years total root biomass was maximum in the maize/soybean intercrop. The surface root dry weight also followed the same trend as maximum root dry weight in the maize/soybean intercrop and minimum root weight in the sole crop soybean. In general, surface roots were dominated by maize roots and subsurface roots were dominated by soybean. Although the nature of significant interaction of log(P) by system at surface in both year was not clear, increased root dry weight in intercrop combination was indicative of more surface intermingling or interference of roots in intercrops. Apart from statistical significance, the root dry weight ratio was generally higher in the intercrop combination than in the sole crop soybean in both years. The high surface to subsurface root dry weight ratio of intercrops combination indicated the predominance of surface intermingling of maize and soybean roots in the mixture. Soybean had the lowest ratio which indicates a deeper rooting pattern than maize.

Though root competition is more important than shoot competition (Donald 1958, Remison and Snaydon 1988, Snaydon and Harris 1981), comparative root studies of intercrops have rarely been accomplished mainly because appropriate techniques are lacking for separating component roots from the mixture.

Schenk and Barber (1979) reported increased shoot yield of corn with increasing P level, but P had little effect on the amount of roots. In my experiment, a similar result was apparent in the intercrop situations. Results of the analysis clearly indicated that total root dry matter ($mg/100\ cm^3$ soil) and root length sampled midway between two rows in intercrops as well as sole crops were not influenced by levels of P concentration in the soil. But the effect of P on surface roots was influenced by different cropping systems. It is not appropriate to conclude that P had no effect on root growth and total root biomass because the variable tested simply denoted a root density in relation to a particular soil volume, i.e., amount of roots in a unit soil volume. Because, specific root sampling sites were used, the roots in the 0 to 0.4 m depth may not be proportional to total roots in the profile. The position of the site deliberately confines the root sample to medium thickness roots and excludes very fine roots beyond the 0.4 m depth and the thick roots near the stem.

Fuseder (1985) and Fuseder et al (1988), using radioautographic methods, studied maize root systems with respect to root competition for macronutrients and found an absence of competition for P in sole as well as in intercrops. The maize roots were randomly distributed and aggregated at special microsites. They observed a maximum number of roots in the top 20 cm soil layer directly below the plant and estimated a root length density of approximately 8 cm/cm^3 soil in that area, with less than 2 cm/cm^3 soil in the rest of the root space. My measurements from the surface and subsurface layers between rows under different systems were to 5.9 to 2.2 and 2.4 to 1.1 cm/cm^3 soil in 1988 and 1989, respectively.

Root antagonism and the tendency of growing root to avoid moisture depleted zones (Litav and Wolovitch 1971, Trenbath 1976) have been suggested as the possible mechanisms of noninterference and stratification of roots in crop mixtures (Leihner 1983). Gregory and Reddy (1982) recorded additional root growth and 10 to 15% more root length in intercropping than sole cropping. However, data from Poamoho indicated that the ratio of roots in surface to subsurface layers was more affected by cropping system than P levels. The interaction of P levels by system for surface roots also suggested that there was greater root interference at the surface. Intercropped systems had 7.5 to 23.2% more roots in the surface and only 3 to 4% more roots in the subsurface layer than sole crop maize for all seasons. Total root dry weight and length at 0 to 0.4 m in the intercrop maize system was 5 to 16% greater than in sole crop maize.

Separation of the roots of two species from intercrop samples posed real problems. Visual identification of maize versus soybean roots was not possible. In intercropping, the roots of the components were indistinguishable and hence the estimated LER were taken as indicative of the intercrop performance. Reddy and Willey (1979) reported LER values up to 1.18, which were very close to my estimates. The LER (an index which indicates the intercropping advantage over sole crop) based on root dry matter could only be calculated in this study if the ratio of component roots was assumed to be the same as above ground dry matter proportion of components in intercropping. Since such an assumption is difficult to verify, a fast and reliable technique to separate roots of different species is needed for a more detailed analysis root in intercropping. The proportion of roots in the surface layer relative to those in the subsurface layer may be a better criteria to quantify the distribution of roots in sole crops and intercrops which influences the intercrop performance. Because the entire root system of intercrop components is near impossible to recover separately, the performance of intercrops compared to sole crops based on root growth has to rely on relative rather than absolute root measurement.

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APPENDICES

Explanations to appendices:

1. Appendices 1 to 11 are cited in the results section of the three chapters. Appendices 12 to 14 are observations taken during the experiment on which statistical analysis were not carried out. Detailed climatic data (for Kauai 1987, Poamoho 1988 and 1989) during the experiments are in appendix 15.
2. Analysis is based on type one sum of squares.
3. Height measurement were recorded by stretching the uppermost leaf. Plant heights are mean of three plants.
4. Methods described in IBSNAT minimum data set were followed in recording growth stages observations.

Abbreviation used in the appendices:

1. M=Sole crop maize, R= Sole crop rice, S=Sole crop soybean, MS= Intercrop maize with soybean, MR=Intercrop maize with rice, and SM= Intercrop soybean with maize.

Appendix 1.1. Combined analysis of variance of maize grain yield (kg/ha) across three environments.

Source of Variation	df	SS/10000	MSS	F Ratio
Corrected Total	117	62826.7		
Environment (Env)	2			
Kauai Vs Poamoho (KVP)	1	4874.6	4874.6	22.5 **
Poamoho88 Vs Poamoho89 (PVP)	1	49805.0	49805.0	229.5 **
Replication(Env)	6	1302.2	217.0	
Phosphorus Level	9	2953.2	328.1	5.6 **
Log(P)	1	2161.4	2161.4	36.8 **
Log(P)*Log(P)	1	6.4	6.4	0.1
Lack of fit	7	785.4	112.2	1.9
Environment*P Level	18	1057.3	58.7	1.0
KVP*Log(P)	1	91.1	91.1	1.6
PVP*Log(P)	1	75.2	75.2	1.3
KVP*Log(P)*Log(P)	1	37.9	37.9	0.6
PVP*Log(P)*Log(P)	1	56.4	56.4	1.0
Lack of fit	14	796.6	56.9	1.0
Rep(Env*P Level)	14	822.6	58.8	
Sole Vs Intercrop (SVI)	1	214.9	214.9	5.0 *
Between Intercrops (INVIN)	1	146.5	146.5	3.4
KVP*SVI	1	9.6	9.6	0.2
PVP*SVI	1	18.3	18.3	0.4
P Level*System	18	344.9	19.2	0.4
Log(P)*SVI	1	38.7	38.7	0.9
Log(P)*INVIN	1	0.0	0.0	0.0
Log(P)*Log(P)*SVI	1	0.1	0.1	0.0
Log(P)*Log(P)*INVIN	1	25.7	25.7	0.6
Lack of fit	14	280.3	20.0	0.5
Env*P Level*System	14	913.5	65.2	1.5
Error	38	1642.0	43.2	

Appendix 1.2. Combined analysis of variance of maize dry matter yield (kg/ha) across three environments.

Source of Variation	df	SS/10000	MSS	F Ratio
Corrected Total	117	559720.0	4783.9	
Environment (Env)	2			
Kauai Vs Poamoho (KVP)	1	88147.9	88147.9	27.6 **
Poamoho88 Vs Poamoho89 (PVP)	1	383155.6	383155.6	120.1 **
Replication (Env)	6	19144.0	3190.7	
Phosphorus Level	9	28573.2	3174.8	5.0
Log(P)	1	22402.1	22402.1	35.4 **
Log(P)*Log(P)	1	62.2	62.2	0.1
Lack of fit	7	6108.9	872.7	1.4
Environment*P Level	18	16075.5	893.1	1.4
KVP*Log(P)	1	2466.5	2466.5	3.9
PVP*Log(P)	1	204.6	204.6	0.3
KVP*Log(P)*Log(P)	1	158.3	158.3	0.3
PVP*Log(P)*Log(P)	1	4302.2	4302.2	6.8
Lack of fit	14	8943.9	638.9	1.0
Rep(Env*P Level)	14	8857.0	632.6	1.6
Sole Vs Intercrop (SVI)	1	4858.6	4858.6	12.5 **
Between Intercrops (INVIN)	1	684.9	684.9	1.8
KVP*SVI	1	2.5	2.5	0.0
PVP*SVI	1	1149.7	1149.7	2.9
P Level*System	18	3827.8	212.7	0.5
Log(P)*SVI	1	31.1	31.1	0.1
Log(P)*INVIN	1	5.7	5.7	0.0
Log(P)*Log(P)*SVI	1	223.0	223.0	0.6
Log(P)*Log(P)*INVIN	1	56.9	56.9	0.1
Lack of fit	14	3511.1	250.8	0.6
Env*P Level*System	14	9662.1	690.1	1.8
Error	38	14816.7	389.9	

Appendix 1.3. Combined analysis of variance of maize harvest index across three environments.

Source of Variation	df	SS*10000	MSS	F Ratio
Corrected Total	117	3074.2	26.3	
Environment (Env)	2			
Kauai Vs Poamoho (KVP)	1	651.2	651.2	
Poamoho88 Vs Poamoho89 (PVP)	1	940.4	940.4	
Replication (Env)	6			
Phosphorus Level	9	176.5	19.6	2.4
Log(P)	1	63.3	63.3	7.6 *
Log(P)*Log(P)	1	0.9	0.9	0.1
Lack of fit	7	112.3	16.0	1.9
Environment*P Level	18	329.7	18.3	2.2
KVP*Log(P)	1	1.2	1.2	0.1
PVP*Log(P)	1	179.6	179.6	21.6 **
KVP*Log(P)*Log(P)	1	2.8	2.8	0.3
PVP*Log(P)*Log(P)	1	19.7	19.7	2.4
Lack of fit	14	126.4	9.0	1.1
Rep(Env*P Level)	14	116.6	8.3	
Sole Vs Intercrop (SVI)	1	34.3	34.3	2.6
Between Intercrops (INVIN)	1	6.0	6.0	0.5
KVP*SVI	1	41.1	41.1	3.1
PVP*SVI	1	14.5	14.5	1.1
P Level*System	18	176.7	9.8	0.7
Log(P)*SVI	1	17.3	17.3	1.3
Log(P)*INVIN	1	5.9	5.9	0.4
Log(P)*Log(P)*SVI	1	6.3	6.3	0.5
Log(P)*Log(P)*INVIN	1	15.1	15.1	1.1
Lack of fit	14	132.0	9.4	0.7
Env*P Level*System	14	89.0	6.4	0.5
Error	38	503.2	13.2	

Appendix 1.4. Combined analysis of variance of maize 100 grain weight across three environments.

Source of Variation	df	SS	MSS	F Ratio
Corrected Total	115	3076.41		
Environment (Env)	2			
Kauai Vs Poamoho (KVP)	1	855.00	855.00	49.5 **
Poamoho88 Vs Poamoho89 (PVP)	1	1779.21	1779.21	103.0 **
Replication (Env)	6	103.67	17.28	
Phosphorus Level	9	189.21	21.02	6.9
Log(P)	1	134.98	134.98	44.1 **
Log(P)*Log(P)	1	7.53	7.53	2.5
Lack of fit	7	46.70	6.67	2.2
Environment*P Level	18	64.48	3.58	1.2
KVP*Log(P)	1	21.37	21.37	7.0 *
PVP*Log(P)	1	2.69	2.69	0.9
KVP*Log(P)*Log(P)	1	7.25	7.25	2.4
PVP*Log(P)*Log(P)	1	0.04	0.04	0.0
Lack of fit	14	33.13	2.37	0.8
Rep(Env*P Level)	14	42.83	3.06	
Sole Vs Intercrop (SVI)	1	7.39	7.39	3.9
Between Intercrops (INVIN)	1	3.26	3.26	1.7
KVP*SVI	1	0.45	0.45	0.2
PVP*SVI	1	5.75	5.75	3.0
P Level*System	18	27.99	1.55	0.8
Log(P)*SVI	1	6.30	6.30	3.3
Log(P)*INVIN	1	0.10	0.10	0.1
Log(P)*Log(P)*SVI	1	0.01	0.01	0.0
Log(P)*Log(P)*INVIN	1	5.92	5.92	3.1
Lack of fit	14	15.66	1.12	0.6
Env*P Level*System	14	32.62	2.33	1.2
Error	36	68.19	1.89	

Appendix 1.5. Combined analysis of variance of maize number of cob per plant across three environments.

Source of Variation	df	SS*10000	MSS	F Ratio
Corrected Total	117	9547.9	81.6	
Environment (Env)	2	3598.7		
Kauai Vs Poamoho (KVP)	1	250.3	250.3	0.0
Poamoho88 Vs Poamoho89 (PVP)	1	3348.4	3348.4	0.1
Replication (Env)	6	179448.0	29908.0	
Phosphorus Level	9	1114.4	123.8	4.5
Log(P)	1	18.1	18.1	0.7
Log(P)*Log(P)	1	264.1	264.1	9.7 **
Lack of fit	7	832.2	118.9	4.4 *
Environment*P Level	18	1682.8	93.5	3.4
KVP*Log(P)	1	31.3	31.3	1.1
PVP*Log(P)	1	32.4	32.4	1.2
KVP*Log(P)*Log(P)	1	306.9	306.9	11.2 **
PVP*Log(P)*Log(P)	1	447.5	447.5	16.4 **
Lack of fit	14	864.7	61.8	2.3
Rep(Env*P Level)	14	382.1	27.3	0.8
Sole Vs Intercrop (SVI)	1	12.8	12.8	0.4
Between Intercrops (INVIN)	1	16.1	16.1	0.5
KVP*SVI	1	46.2	46.2	1.4
PVP*SVI	1	7.2	7.2	0.2
P Level*System	18	934.7	51.9	1.6
Log(P)*SVI	1	0.4	0.4	0.0
Log(P)*INVIN	1	129.3	129.3	3.9
Log(P)*Log(P)*SVI	1	1.3	1.3	0.0
Log(P)*Log(P)*INVIN	1	47.6	47.6	1.4
Lack of fit	14	756.2	54.0	1.6
Env*P Level*System	14	448.4	32.0	1.0
Error	38	1271.0	33.4	

Appendix 1.6. Combined analysis of variance of maize cob length across three environments.

Source of Variation	df	SS	MSS	F Ratio
Corrected Total	117	1505.91		
Environment (Env)	2			
Kauai Vs Poamoho (KVP)	1	208.75	208.75	0.1
Poamoho88 Vs Poamoho89 (PVP)	1	956.60	956.60	0.5
Replication (Env)	6	10898.22	1816.37	
Phosphorus Level	9	79.59	8.84	3.7
Log(P)	1	58.02	58.02	24.5 **
Log(P)*Log(P)	1	8.89	8.89	3.8
Lack of fit	7	12.68	1.81	0.8
Environment*P Level	18	64.46	3.58	1.5
KVP*Log(P)	1	1.61	1.61	0.7
PVP*Log(P)	1	16.83	16.83	7.1
KVP*Log(P)*Log(P)	1	4.27	4.27	1.8
PVP*Log(P)*Log(P)	1	9.86	9.86	4.2
Lack of fit	14	31.88	2.28	1.0
Rep(Env*P Level)	14	33.15	2.37	
Sole Vs Intercrop (SVI)	1	9.38	9.38	4.0
Between Intercrops (INVIN)	1	5.78	5.78	2.5
KVP*SVI	1	1.74	1.74	0.8
PVP*SVI	1	0.77	0.77	0.3
P Level*System	18	15.22	0.85	0.4
Log(P)*SVI	1	0.20	0.20	0.1
Log(P)*INVIN	1	0.69	0.69	0.3
Log(P)*Log(P)*SVI	1	0.61	0.61	0.3
Log(P)*Log(P)*INVIN	1	0.08	0.08	0.0
Lack of fit	14	13.63	0.97	0.4
Env*P Level*System	14	37.4	2.67	1.2
Error	38	88.02	2.32	

Appendix 1.7. Combined analysis of variance of maize number of kernel rows across three environments.

Source of Variation	df	SS	MSS	F Ratio
Corrected Total	117	160.02		
Environment (Env)	2			
Kauai Vs Poamoho (KVP)	1	83.88	83.88	128.6 **
Poamoho88 Vs Poamoho89 (PVP)	1	4.12	4.12	6.3 *
Replication (Env)	6	3.91	0.65	
Phosphorus Level	9	22.77	2.53	6.8
Log(P)	1	16.83	16.83	45.1 **
Log(P)*Log(P)	1	0.10	0.10	0.3
Lack of fit	7	5.84	0.83	2.2
Environment*P Level	18	11.04	0.61	1.6
KVP*Log(P)	1	1.96	1.96	5.3 *
PVP*Log(P)	1	3.10	3.10	8.3 **
KVP*Log(P)*Log(P)	1	0.00	0.00	0.0
PVP*Log(P)*Log(P)	1	0.08	0.08	0.2
Lack of fit	14	5.90	0.42	1.1
Rep(Env*P Level)	14	5.22	0.37	
Sole Vs Intercrop (SVI)	1	0.00	0.00	0.0
Between Intercrops (INVIN)	1	0.68	0.68	1.8
KVP*SVI	1	0.00	0.00	0.0
PVP*SVI	1	0.49	0.49	1.3
P Level*System	18	10.09	0.56	1.5
Log(P)*SVI	1	0.23	0.23	0.6
Log(P)*INVIN	1	0.23	0.23	0.6
Log(P)*Log(P)*SVI	1	1.50	1.50	4.1
Log(P)*Log(P)*INVIN	1	0.71	0.71	1.9
Lack of fit	14	7.42	0.53	1.4
Env*P Level*System	14	7.6	0.54	1.5
Error	38	13.99	0.37	

Appendix 2.1. Combined analysis of variance of soybean grain yield (kg/ha) across two season at Poamoho.

Source of variation	df	SS/10000	MSS	F-ratio
Corrected Total	59	6662.5		
Environment	1	435.7	435.7	2.8
Replication (Env)	4	618.1	154.5	
Phosphorus Level	9	370.0	41.1	2.6 **
Log(P)	1	126.5	126.5	7.9 **
Log(P)*Log(P)	1	0.0	0.0	0.0
Lack of fit	7	243.4	34.8	2.2
Environment*P Level	9	317.1	35.2	2.2
Env*Log(P)	1	10.9	10.9	0.7
Env*Log(P)*Log(P)	1	8.3	8.3	0.4
Lack of fit	7	297.9	42.6	2.6
Rep(Env*P Level)	8	128.5	16.1	
System	1	4073.7	4073.7	290.9 **
Environment*System	1	838.5	838.5	59.9 **
P Level*System	9	281.2	31.2	2.2
Log(P)*System	1	213.0	213.0	15.2 **
Log(P)*Log(P)*System	1	20.8	20.8	1.5
Lack of fit	7	47.4	6.8	0.5
Env*P Level*System	5	115.3	23.1	1.6
Env*Log(P)*System	1	26.4	26.4	1.9
Lack of fit	4	89.0	22.2	1.6
Error	16	224.0	14.0	

Appendix 2.2. Combined analysis of variance of soybean dry matter yield (kg/ha) across two season at Poamoho.

Source of variation	df	SS/10000	MSS	F-ratio
Corrected Total	59	41301.4		
Environment	1	13549.8	13549.8	9.7 **
Replication (Env)	4	5565.6	1391.4	
Phosphorus Level	9	2982.4	331.4	1.3
Log(P)	1	1728.9	1728.9	6.5 **
Log(P)*Log(P)	1	6.1	6.1	0.0
Lack of fit	7	1247.5	178.2	0.7
Environment*P Level	9	2151.5	239.1	0.9
Env*Log(P)	1	17.7	17.7	0.1
Env*Log(P)*Log(P)	1	202.2	202.2	0.8
Lack of fit	7	1931.5	275.9	1.0
Rep(Env*P Level)	8	2114.2	264.3	
System	1	14061.6	14061.6	216.3 **
Environment*System	1	2547.4	2547.4	39.2 **
P Level*System	9	1868.8	207.6	3.2
Log(P)*System	1	971.9	971.9	14.9 **
Log(P)*Log(P)*System	1	0.5	0.5	0.0
Lack of fit	7	896.5	128.1	2.0
Env*P Level*System	5	1222.2	244.4	3.8
Env*Log(P)*System	1	179.0	179.0	2.8
Lack of fit	4	1043.2	260.8	4.0
Error	16	1040.3	65.0	

Appendix 2.3. Combined analysis of variance of soybean harvest index across two season at Poamoho.

Source of variation	df	SS*10000	MSS	F ratio
Corrected Total	59	4353.3		
Environment (Env)	1	1507.3	1507.3	
Replication (Env)	4			
Phosphorus Level	9	588.0	65.3	1.73
Log(P)	1	168.6	168.6	4.46
log(P)*Log(P)	1	47.8	47.8	1.26
Lack of fit	7	371.7	53.1	1.40
Environment*P Level	9	285.4	31.7	0.84
Env*Log(P)	1	1.2	1.2	0.03
Env*Log(P)*Log(P)	1	69.6	69.6	1.33
Lack of fit	7	214.7	30.7	0.81
Rep(Env*P Level)	8	302.8	37.8	
System	1	947.0	947.0	37.49 **
Environment*System	1	158.9	158.9	6.29 *
P Level*System	9	169.1	18.8	0.74
Log(P)*System	1	19.7	19.7	0.78
Log(P)*Log(P)*system	1	52.4	52.4	2.08
Lack of fit	7	96.9	13.8	0.55
Env*P Level*System	5	34.7	6.9	0.27
Env*Log(P)*System	1	17.4	17.4	0.69
Lack of fit	4	17.3	4.3	0.17
Error	16	404.2	25.3	

Appendix 2.4. Combined analysis of variance of soybean 100 grain weight across two season at Poamoho.

Source of variation	df	SS	MSS	F-ratio
Corrected Total	59	432.7		
Environment (Env)	1	40.1	40.1	4.6
Replication (Env)	4	35.0	8.8	
Phosphorus Level	9	24.7	2.7	3.2
Log(P)	1	2.9	2.9	3.4
Log(P)*Log(P)	1	0.9	0.9	1.0
Lack of fit	7	20.9	3.0	3.5
Environment*P Level	9	24.3	2.7	3.2
Env*Log(P)	1	7.1	7.1	8.3 *
Env*Log(P)*Log(P)	1	0.2	0.2	0.0
Lack of fit	7	16.9	2.4	2.8
Rep(Env*P Level)	8	6.8	0.9	
System	1	234.9	234.9	198.0 **
Environment*System	1	48.6	48.6	41.0 **
P Level*System	9	31.2	3.5	2.9
Log(P)*System	1	3.6	3.6	3.1
Log(P)*Log(P)*System	1	6.6	6.6	5.5 *
Lack of fit	7	21.0	3.0	2.5
Env*P Level*System	5	4.9	1.0	0.8
Env*Log(P)*System	1	2.5	2.5	2.1
Lack of fit	4	2.4	0.6	0.5
Error	16	19.0	1.2	

Appendix 3.1. Analysis of variance of soybean dry matter (g/m^2) across growth stages at Poamoho 1988.

Source of variation	df	SS	MSS	F ratio
Corrected Total	95	6735066.5		
Phosphorus Level	9	574849.5	63872.2	29.8 **
Log(P)	1	220780.7	220780.7	103.1 **
Log(P)*Log(P)	1	3825.7	3825.7	1.8
Lack of fit	7	350243.1	50034.7	23.4
System	1	1420655.4	1420655.4	663.1 **
P Level*System	5	350232.6	70046.5	32.7
Log(P)*System	1	65310.4	65310.4	30.5 **
Log(P)*Log(P)*System	1	4619.1	4619.1	2.2
Lack of fit	3	280303.1	93434.4	43.6 **
Rep(Log(P)*System)	4	8573.53	2143.4	
Date	3	3076548.3	1025516.1	45.6 **
Date (linear)	1	2698702.7	2698702.7	119.9 **
Date*Date	1	139968.6	139968.6	6.2
Lack of fit	1	237877.0	237877.0	10.6 **
Rep(Date)	3	67515.7	22505.2	
P-Level*Date	27	313996.8	11629.5	2.8
Log(P)*Date	1	83455.3	83455.3	20.3 *
Log(P)*Log(P)*Date	1	5571.1	5571.1	1.4
Log(P)*Date*Date	1	6461.0	6461.0	1.6
Lack of fit	24	218509.3	9104.6	2.2
System*Date	3	545486.5	181828.8	44.2 **
P-Level*System*Date	15	274308.7	18287.2	4.4
Error	25	102889.5	4115.6	

Appendix 3.2. Analysis of variance of soybean dry matter (g/m^2) across growth stages at Poamoho 1989.

Source of variation	df	SS	MSS	F ratio
Corrected Total	95	5631015.2		
Phosphorus Level	9	125800.5	13977.8	17.3 **
Log(P)	1	106210.6	106210.6	131.8 **
Log(P)*Log(P)	1	23.7	23.7	0.0
Lack of fit	7	19566.2	2795.2	3.5
System	1	1721737.6	1721737.6	2136.1 **
P Level*System	9	77811.1	8645.7	10.7 **
Log(P)*System	1	59300.6	59300.6	73.6 **
Log(P)*Log(P)*System	1	3537.6	3537.6	4.4
Lack of fit	7	14972.9	2139.0	2.7
Rep(Log(P)*System)	8	6448.2	806.0	
Date	3	2223843.5	741281.2	153.4 **
Date (Linear)	1	2203882.4	2203882.4	455.9 **
Date*Date	1	19961.0	19961.0	4.1
Lack of fit	1	0.0	0.0	0.0
Rep(Date)	3	14501.4	4833.8	
P-Level*Date	27	123004.0	4555.7	1.4
Log(P)*Date	1	52993.6	52993.6	16.2 **
Log(P)*Log(P)*Date	1	1250.9	1250.9	0.4
Log(P)*Date*Date	1	332.5	332.5	0.1
Lack of fit	24	68427.0	2851.1	0.9
System*Date	3	1051095.4	350365.1	107.4 **
P-Level*System*Date	27	113883.5	4217.9	1.3
Error	53	172890.0	3262.1	

Appendix 4.1. Analysis of variance of maize dry matter (g/m^2) across growth stages at Kauai.

Source of variation	df	SS	MSS	F ratio
Corrected Total	159	23693224.7		
Phosphorus Level	9	343123.0	38124.8	1.1
Log(P)	1	115520.6	115520.6	3.3 *
Log(P)*Log(P)	1	508.1	508.1	0.0
Lack of fit	7	227094.3	32442.0	0.9
System	1	372676.3	372676.3	10.6 **
P Level*System	9	256821.1	51364.2	1.5
Log(P)*System	1	13.9	13.9	0.0
Lack of fit	8	256807.2	32100.9	0.9
Rep(Log(P)*System)	12	420201.1	35016.8	
Date	3	20469780.1	6823260.0	439.8 **
Date (Linear)	1	20262624.7	20262624.7	1306.1 **
Date*Date	1	115994.5	115994.5	7.5
Lack of fit	1	91160.9	91160.9	5.9
Rep(Date)	3	46540.2	15513.4	
P-Level*Date	27	414273.2	15343.5	9.7 **
Log(P)*Date	1	122870.6	122870.6	77.6 **
Log(P)*Log(P)*Date	1	1516.4	1516.4	1.0
Log(P)*Date*Date	1	6461.0	6461.0	4.1
Lack of fit	24	283425.2	11809.4	7.5
System*Date	3	163718.2	54572.7	34.5 **
P-Level*System*Date	27	297506.2	11018.7	7.0
Error	65	102889.5	1582.9	

Appendix 4.2. Analysis of variance of maize dry matter (g/m^2) across growth stages at Poamoho 1988.

Source of variation	df	SS	MSS	F ratio
Corrected Total	164	28116071.5		
Phosphorus Level	9	1172549.0	130283.2	6.7
Log(P)	1	575877.9	575877.9	29.8 **
Log(P)*Log(P)	1	309748.5	309748.5	16.0 **
Lack of fit	7	286922.7	40989.0	2.1
System	2	148152.7	74076.3	3.8
Sole VS Intercrop(SVI	1	142944.7	142944.7	7.4 *
Between Intercrop(INVIN)	1	9221.6	9221.6	0.5
P Level*System	14	367471.7	26248.0	1.4
Log(P)*SVI	1	10970.8	10970.8	0.6
Log(P)*INVIN	1	816.9	816.9	0.0
Lack of fit	12	355684.1	29640.3	1.5
Rep(Log(P)*System)	8	154763.4	19345.4	
Date	3	22838781.0	7612927.0	490.7 **
Date (Linear)	1	22159291.5	22159291.5	1428.4 **
Date*Date	1	79406.1	79406.1	5.1
Lack of fit	1	600083.4	600083.4	38.7
Rep(Date)	3	27060.9	9020.3	
P-Level*Date	27	1005361.9	37235.6	1.5
Log(P)*Date	1	445559.6	445559.6	17.5 **
Log(P)*Log(P)*date	1	125771.2	125771.2	4.9
Log(P)*Date*Date	1	75725.3	75725.3	3.0
Lack of fit	24	358305.9	14929.4	0.6
System*Date	6	484550.1	80758.3	3.2
SVI*Date	1	111162.7	111162.7	4.4 *
INVIN*Date	1	387.0	387.0	0.0
P-Level*System*Date	39	569224.6	14595.5	0.6
Error	53	1348156.3	25436.9	

Appendix 4.3. Analysis of variance of maize dry matter (g/m^2) across growth stages at Poamoho 1989.

Source of variation	df	SS	MSS	F ratio
Corrected Total	143	115893506.1		
Phosphorus Level	9	1839262.5	204362.5	4.8 *
Log(P)	1	1437978.9	1437978.9	34.1 **
Log(P)*Log(P)	1	7747.2	7747.2	0.2
Lack of fit	7	393536.3	56219.5	1.3
System	1	88571.2	88571.2	2.1
P Level*System	9	223495.9	24832.9	0.6
Log(P)*System	1	44068.2	44068.2	1.0
Lack of fit	8	179427.7	22428.5	0.5
Rep(Log(P)*System)	8	337428.8	42178.6	
Date	3	110362290.1	36787430.0	3716.0 **
Date (Linear)	1	102214528.7	102214528.7	10325.0 **
Date*Date	1	7568189.0	7568189.0	764.5 **
Lack of fit	1	579572.4	579572.4	58.5 **
Rep(Date)	3	29699.2	9899.7	
P-Level*Date	27	1567476.9	58054.7	3.2
Log(P)*Date	1	620336.1	620336.1	34.2 **
Log(P)*Log(P)*Date	1	88390.2	88390.2	4.9
Log(P)*Date*Date	1	51.9	51.9	0.0
Lack of fit	24	858698.8	35779.1	2.0
System*Date	3	47733.4	15911.1	0.9
P-Level*System*Date	27	435131.7	16116.0	0.9
Error	53	962416.4	18158.8	

Appendix 5.1.1. Analysis of variance of maize leaf dry weight (g/m^2) across days after planting at Poamoho 1988.

Sources of variation	df	SS	MSS	F ratio
Corrected Total	165			
Phosphorus Level	9	25128.9	2792.1	9.0 **
Log(P)	1	6028.3	6028.3	19.3 **
Log(P)*Log(P)	1	8275.2	8275.2	26.5 **
Lack of fit	7	10825.4	1546.5	5.0
System	2	881.7	440.9	1.4
P Level*System	14	10601.5	757.2	2.4
Rep(P Level*System)	8	2495.6	312.0	
Date	3	405703.7	135234.6	206.9 **
Rep(Date)	3	1960.6	653.5	
P Level*Date	27	34923.2	1293.5	1.9
System*Date	6	2948.7	491.5	0.7
P Level*System*Date	40	22957.4	573.9	0.8
Error	53	36550.5	689.6	

Appendix 5.1.2. Analysis of variance of maize leaf dry weight (g/m2) across days after planting at Poamoho 1989.

Sources of variation	df	SS	MSS	F ratio
Corrected Total	107			
Phosphorus Level	9	35763.7	3973.7	3.5
Log(P)	1	27259.7	27259.7	23.7 **
Log(P)*Log(P)	1	2364.3	2364.3	2.1
Lack of fit	7	6139.7	877.1	0.8
System	1	7054.2	7054.2	6.1
P Level*System	9	5892.8	654.8	0.6
Rep(P Level*System)	8	9203.0	1150.4	
Date	2	873778.2	436889.1	1893.6 **
Rep(Date)	2	461.4	230.7	
P Level*Date	18	14729.2	818.3	1.4
System*Date	2	2745.6	1372.8	2.3
P Level*System*Date	18	8209.4	456.1	0.8
Error	38	22364.1	588.5	

Appendix 5.2.1. Analysis of variance of maize leaf area index at Poamoho 1988 across days after planting.

Sources of variation	df	SS	MSS	F ratio
Corrected Total	165			
Phosphorus Level	9	5.1	0.6	11.1 **
Log(P)	1	0.9	0.9	17.8 **
Log(P)*Log(P)	1	1.7	1.7	32.2 **
Lack of fit	7	2.5	0.4	7.1
System	2	0.2	0.1	2.0
P Level*System	14	1.9	0.1	2.6
Rep(P Level*System)	8	0.4	0.1	
Date	3	69.5	23.2	169.6 **
Rep(Date)	3	0.4	0.1	
P Level*Date	27	7.4	0.3	1.8
System*Date	6	0.6	0.1	0.7
P Level*System*Date	40	4.2	0.1	0.7
Error	53	8.0	0.2	

Appendix 5.2.2. Analysis of variance of maize leaf area index at Poamoho 1989 across days after planting.

Sources of variation	df		SS	MSS	F ratio	
Corrected Total	107					
Phosphorus Level	9		5.2	0.6	2.2	
Log(P)		1	3.0	3.0	11.4	**
Log(P)*Log(P)		1	0.4	0.4	1.5	
Lack of fit		7	1.8	0.3	1.0	
System	1		1.0	1.0	3.7	
P Level*System	9		0.7	0.1	0.3	
Rep(P Level*System)	8		2.1	0.3		
Date	2		209.8	104.9	6993.7	**
Rep(Date)	2		0.0	0.0		
P Level*Date	18		4.2	0.2	1.6	
System*Date	2		0.5	0.3	1.7	
P Level*System*Date	18		1.2	0.1	0.4	
Error	38		5.7	0.1		

Appendix 5.3.1. Analysis of variance of maize specific leaf area at Poamoho 1988 across days after planting.

Sources of variation	df		SS	MSS	F ratio	
Corrected Total	165					
Phosphorus Level	9		49479.5	5497.7	0.8	
Log(P)		1	22587.4	22587.4	3.4	
Log(P)*Log(P)		1	7308.5	7308.5	1.1	
Lack of fit		7	19583.6	2797.7	0.4	
System	2		6029.3	3014.6	0.4	
P Level*System	14		35805.0	2557.5	0.4	
Rep(P Level*System)	8		53913.1	6739.1		
Date	3		199525.8	66508.6	11.5	**
Rep(Date)	3		17312.0	5770.7		
P Level*Date	27		49794.3	1844.2	0.6	
System*Date	6		4062.2	677.0	0.2	
P Level*System*Date	40		45635.2	1140.9	0.4	
Error	53		154634.8	2917.6		

Appendix 5.3.2. Analysis of variance of maize specific leaf area at Poamoho 1989 across days after planting.

Sources of variation	df		SS	MSS	F ratio	
Corrected Total	107					
Phosphorus Level	9		8485.6	942.8	4.1	
Log(P)		1	4977.2	4977.2	21.6	**
Log(P)*Log(P)		1	218.2	218.2	0.9	
Lack of fit		7	3290.3	470.0	2.0	
System	1		430.1	430.1	1.9	
P Level*System	14		3163.7	226.0	1.0	
Rep(P Level*System)	8		1844.1	230.5		
Date	2		116614.6	58307.3	2212.0	**
Rep(Date)	2		52.7	26.4		
P Level*Date	18		4392.6	244.0	1.5	
System*Date	2		661.7	330.8	2.0	
P Level*System*Date	18		5002.6	277.9	1.7	
Error	38		6247.1	164.4		

Appendix 6.1.1. Analysis of variance of soybean leaf dry weight (g/m^2) across days after planting at Poamoho 1988.

Sources of variation	df	SS	MSS	F ratio
Corrected Total	71			
Phosphorus Level	9	6708.6	745.4	25.5 **
Log(P)	1	3159.9	3159.9	108.1 **
Log(P)*Log(P)	1	763.0	763.0	26.1 **
Lack of fit	7	2785.6	397.9	13.6
System	1	23389.1	23389.1	799.9 **
P Level*System	5	5986.4	1197.3	40.9 **
Rep(P Level*System)	4	117.0	29.2	
Date	2	38710.3	19355.2	173.2 **
Rep(Date)	2	223.5	111.7	
P Level*Date	18	3586.3	199.2	2.3
System*Date	2	8043.4	4021.7	46.5 **
P Level*System*Date	10	3508.5	350.9	4.1
Error	18	1557.9	86.6	

Appendix 6.1.2. Analysis of variance of soybean leaf dry weight (g/m2) across days after planting at Poamoho 1989.

Sources of variation	df	SS	MSS	F ratio
Corrected Total	107			
Phosphorus Level	9	9618.0	1068.7	2.9
Log(P)	1	5709.1	5709.1	15.5 **
Log(P)*Log(P)	1	125.7	125.7	0.3
Lack of fit	7	3783.1	540.4	1.5
System	1	91672.7	91672.7	248.8 **
P Level*System	9	7095.7	788.4	2.1
Rep(P Level*System)	8	2947.1	368.4	
Date	2	80988.1	40494.1	61.2 **
Rep(Date)	2	1323.3	661.6	
P Level*Date	18	6814.3	378.6	2.4
System*Date	2	43689.1	21844.6	139.2 **
P Level*System*Date	18	7793.0	432.9	2.8
Error	38	5962.2	156.9	

Appendix 6.2.1. Analysis of variance of soybean leaf area index across days after planting at Poamoho 1988.

Sources of variation	df	SS	MSS	F ratio
Corrected Total	69			
Phosphorus Level	9	6.0	0.7	11.3 **
Log(P)	1	2.6	2.6	43.9 **
Log(P)*Log(P)	1	0.5	0.5	7.9 **
Lack of fit	7	2.9	0.4	7.1
System	1	21.1	21.1	358.1 **
P Level*System	5	8.6	1.7	29.3 **
Rep(P Level*System)	4	0.2	0.1	
Date	2	24.9	12.5	519.4 **
Rep(Date)	2	0.0	0.0	(< .1)
P Level*Date	18	2.7	0.1	0.3
System*Date	2	5.2	2.6	5.6
P Level*System*Date	9	3.7	0.4	0.9
Error	17	8.0	0.5	

Appendix 6.2.2. Analysis of variance of soybean leaf area index across days after planting at Poamoho 1989.

Sources of variation	df	SS	MSS	F ratio
Corrected Total	105			
Phosphorus Level	9	9.4	1.0	4.7
Log(P)	1	6.5	6.5	29.3 **
Log(P)*Log(P)	1	0.1	0.1	0.3
Lack of fit	7	2.8	0.4	1.8
System	1	70.9	70.9	320.6 **
P Level*System	9	6.8	0.8	3.4
Rep(P Level*System)	8	1.8	0.2	
Date	2	81.2	40.6	122.3 **
Rep(Date)	2	0.7	0.3	
P Level*Date	18	6.6	0.4	2.9
System*Date	2	32.7	16.3	128.3 **
P Level*System*Date	17	6.0	0.4	2.8
Error	37	4.7	0.1	

Appendix 6.3.1. Analysis of variance of soybean specific leaf area across days after planting at Poamoho 1988.

Sources of variation	df	SS	MSS	F ratio
Corrected Total	69			
Phosphorus Level	9	22150.8	2461.2	0.6
Log(P)	1	308.2	308.2	0.1
Log(P)*Log(P)	1	453.8	453.8	0.1
Lack of fit	7	21388.8	3055.5	0.7
System	1	2844.6	2844.6	0.7
P Level*System	5	9440.0	1888.0	0.4
Rep(P Level*System)	4	16941.2	4235.3	
Date	2	90602.0	45301.0	11.0 **
Rep(Date)	2	8245.8	4122.9	
P Level*Date	18	45061.2	2503.4	0.3
System*Date	2	180.5	90.2	0.0
P Level*System*Date	9	20297.5	2255.3	0.3
Error	17	122464.4	7203.8	

Appendix 6.3.2. Analysis of variance of soybean specific leaf area across days after planting at Poamoho 1988.

Sources of variation	df	SS	MSS	F ratio
Corrected Total	105			
Phosphorus Level	9	45810.6	5090.1	0.8
Log(P)	1	4169.2	4169.2	0.7
Log(P)*Log(P)	1	1090.9	1090.9	0.2
Lack of fit	7	40550.5	5792.9	0.9
System	1	214661.6	214661.6	33.5 **
P Level*System	9	41367.0	4596.3	0.7
Rep(P Level*System)	8	51248.0	6406.0	
Date	2	317466.7	158733.4	77.3 **
Rep(Date)	2	4104.7	2052.4	
P Level*Date	18	48738.2	2707.7	0.5
System*Date	2	94356.9	47178.4	8.3 **
P Level*System*Date	17	36449.6	2144.1	0.4
Error	37	210612.1	5692.2	

Appendix 7.1. Combined analysis of variance of maize leaf punch (% P) across different days after planting and across three environments.

Sources of variation	df	SS*1000	MSS	F ratio
Corrected Total	429	3836.8		
Environment (Env)	2	275.7	137.8	159.0
Kauai Vs Poamoho (KVP)	1	59.2	59.2	68.3
Poamoho88 Vs Poamoho89 (PVP)	1	216.4	216.4	249.6
Replication (Env)	6			
Phosphorus Level	9	698.2	77.6	89.5 **
Log(P)	1	666.4	666.4	768.5 **
Log(P)*Log(P)	1	7.4	7.4	8.5 **
Lack of fit	7	24.4	3.5	4.0
Environment*P Level	18	321.3	17.8	20.6 **
KVP*Log(P)	1	133.2	133.2	153.6 **
PVP*Log(P)	1	115.9	115.9	133.6 **
KVP*Log(P)*Log(P)	1	4.3	4.3	4.9 *
PVP*Log(P)*Log(P)	1	8.6	8.6	9.9 **
KVP*Log(P)*Log(P)*Log(P)	1	1.1	1.1	1.3
PVP*Log(P)*Log(P)*Log(P)	1	0.0	0.0	0.0
Lack of fit	14	58.3	4.2	4.8 *
Rep(Environment*P Level)	14	12.1	0.9	
System (SYS)	2	6.2	3.1	1.4
Sole Vs Intercrop (SVI)	1	2.5	2.5	1.1
Between Intercrops (INVIN)	1	2.9	2.9	1.3
Environment*System	2	12.7	6.4	2.8
KVP*SVI	1	1.1	1.1	0.5
PVP*SVI	1	14.2	14.2	6.3 *
P Level*System	18	38.5	2.1	0.9
Log(P)*SVI	1	0.3	0.3	0.1
Log(P)*INVIN	1	1.8	1.8	0.8
Log(P)*Log(P)*SVI	1	2.0	2.0	0.9
Log(P)*Log(P)*INVIN	1	3.4	3.4	1.5
Lack of fit	14	31.1	2.2	1.0
Environment*P Level*System	14	30.1	2.2	1.0
Rep(Environment*P Level*SYS)	14	31.7	2.3	
Date	3	763.8	254.6	21.0 *
Date (Linear)	1	697.9	697.9	57.6 **
Date*Date	1	3.4	3.4	0.3
Lack of fit	1	62.5	62.5	5.2
Replication*Date	3	36.3	12.1	
Environment*Date	5	335.1	67.0	41.3 **
KVP*Date	1	48.4	48.4	29.9
PVP*Date	1	17.6	17.6	10.9
Lack of fit	3	269.0	89.7	55.3
P Level*Date	27	339.1	12.6	7.7 **
Log(P)*Date (Linear)	1	128.5	128.5	79.2 **
Log(P)*Log(P)*Date	1	0.9	0.9	0.6
Log(P)*Date*Date	1	160.8	160.8	99.2 **
Lack of fit	24	48.8	2.0	1.3
System*Date	6	2.2	0.4	0.2
Environment*P Level*Date	45	504.5	11.2	6.9 **
KVP*P Level*Date	1	4.2	4.2	2.6
PVP*P Level*Date	1	307.5	307.5	189.6 **
Lack of fit	43	192.8	4.5	2.8
Environment*System*Date	5	5.9	1.2	0.7
P Level*System*Date	54	140.7	2.6	1.6
Environment*P Level*System*Date	32	29.5	0.9	0.6
Error	56	253.0	1.6	

Appendix 7.2. Combined analysis of variance of soybean leaf punch (% P) at different days after planting across two season at Poamoho.

Sources of variation	df	SS*1000	MSS	F ratio
Corrected Total	237			
Environments (Env)	1	0.3	0.3	0.1
Replication (Env)	4			
Phosphorus Level	9	924.7	102.7	28.8 **
Log(P)	1	722.4	722.4	202.3 **
Log(P)*Log(P)	1	141.4	141.4	39.6 **
Lack of fit	7	61.0	8.7	2.4
Environment*P Level	9	302.6	33.6	9.4 **
Environment*Log(P)	1	275.1	275.1	77.1 **
Lack of fit	8	27.5	3.4	1.0
Rep(Env*P Level)	8	28.5	3.6	
System (SYS)	1	0.6	0.6	0.3
Environment*System	1	14.6	14.6	6.4
P Level*System	9	14.7	1.6	0.7
Log(P)*System	1	0.0	0.0	0.0
Lack of fit	8	14.6	1.8	0.8
Environment*P Level*System	5	18.1	3.6	1.6
Rep(ENV*P Level*System)	9	20.5	2.3	
Date	3	552.6	184.2	12.7 *
Date (Linear)	1	525.6	525.6	36.1 **
Date*Date	1	7.8	7.8	0.5
Lack of fit	1	19.2	19.2	1.3
Replication*Date	3	43.7	14.6	
Environment*Date	3	1276.0	425.3	281.7 **
Environment*Date (Linear)	1	868.2	868.2	575.0 **
Environment*Date*Date	1	20.9	20.9	13.8 **
Lack of fit	1	387.0	387.0	256.3 **
P Level*Date	27	381.9	127.3	84.3 **
Log(P)*Date (Linear)	1	123.2	123.2	81.6 **
Log(P)*Log(P)*Date	1	45.1	45.1	29.9 **
Log(P)*Date*Date	1	59.2	59.2	39.2 **
Lack of fit	24	154.4	6.4	4.3 **
System*Date	3	16.0	5.3	3.5 *
System*Date (Linear)	1	6.2	6.2	4.1 *
Lack of fit	2	9.8	4.9	3.2 *
Environment*P Level*Date	27	235.3	8.7	5.8 **
Environment*System*Date	3	16.3	5.4	3.6 *
P Level*System*Date	27	112.3	4.2	2.8 **
Environment*P Level*System*Date	14	34.4	2.5	1.6
Error	80	120.9	1.5	

Appendix 8.1.1. Analysis of variance of soybean Leaf punch (% P) across different days after planting at Poamoho 1988.

Source of variation	df	SS*1000	MSS	F ratio
Corrected Total	69	2152.2		
Phosphorus Level	9	1075.6	119.5	17.6 *
Log(P)	1	936.9	936.9	137.8 *
Log(P)*Log(P)	1	68.4	68.4	10.1 *
Lack of fit	7	70.3	10.0	1.5
System	1	5.8	5.8	0.9
P Level*System	5	13.1	2.6	0.4
Log(P)*System	1	0.9	0.9	0.1
Log(P)*Log(P)*System	1	12.0	12.0	1.8
Lack of fit	3	0.2	0.1	0.0
Rep(P Level)*System)	4	27.2	6.8	
Date	3	385.2	128.4	8.4 *
Date (linear)	1	77.9	77.9	5.1
Date*Date	1	4.7	4.7	0.3
Lack of fit	1	302.6	302.6	19.9
Rep(Date)	3	45.6	15.2	
P Level*Date	27	455.1	16.9	9.9 *
Log(P)*Date	1	121.1	121.1	71.2 *
Log(P)*Log(P)*Date	1	49.4	49.4	29.1 *
Log(P)*Date*Date	1	17.8	17.8	10.5 *
Lack of fit	24	266.8	11.1	6.5
System*Date	3	28.4	9.5	5.6 *
P Level*System*Date	14	75.2	5.4	3.2 *
Error	24	41.0	1.7	

Appendix 8.1.2. Analysis of variance of soybean Leaf punch (% P) across different days after planting at Poamoho 1989.

Source of variation	df	SS*1000	MSS	F ratio
Corrected Total	143	1938.3		
Phosphorus Level	9	151.7	16.9	30.6
Log(P)	1	93.5	93.5	170.0 *
Log(P)*Log(P)	1	44.8	44.8	81.5 *
Lack of fit	7	13.4	1.9	3.5
System	1	2.4	2.4	4.4
P Level*System	9	21.0	2.3	4.2 *
Log(P)*System	1	1.4	1.4	2.5
Log(P)*Log(P)*System	1	0.0	0.0	0.1
Lack of fit	7	19.6	2.8	5.1
Rep(P Level)*System)	8	4.4	0.6	
Date	3	1442.9	481.0	80.2 *
Date (linear)	1	1320.0	1320.0	220.0 *
Date*Date	1	22.2	22.2	3.7
Lack of fit	1	100.7	100.7	16.8
Rep(Date)	3	16.6	5.5	
P Level*Date	27	139.4	5.2	3.4 *
Log(P)*Date	1	28.1	28.1	18.7 *
Log(P)*Log(P)*Date	1	6.2	6.2	4.1 *
Log(P)*Date*Date	1	41.6	41.6	27.7 *
Lack of fit	24	63.5	2.6	1.8
System*Date	3	9.1	3.0	2.0
P Level*System*Date	27	71.4	2.6	1.8
Error	53	79.5	1.5	

Appendix 8.2.1. Analysis of variance of maize Leaf punch (% P) across different days after planting at Kauai.

Source of variation	df	SS*1000	MSS	F ratio
Corrected Total	118	730.2		
Phosphorus Level	9	48.0	5.3	2.3
Log(P)	1	12.5	12.5	5.4 *
Log(P)*Log(P)	1	0.0	0.0	0.0
Lack of fit	7	35.5	5.1	2.2
System	1	5.2	5.2	2.3
P Level*System	9	14.0	2.8	1.2
Log(P)*System	1	0.1	0.1	0.0
Lack of fit	8	13.9	1.7	0.8
Rep(P Level*System)	12	27.9	2.3	
Date	2	448.4	149.5	15.6 *
Rep(Date)	2	19.2	9.6	
P Level*Date	18	50.9	1.9	0.9
Log(P)*Date	1	3.8	3.8	1.7
Log(P)*Log(P)*Date	1	5.2	5.2	2.4
Log(P)*Date*Date	1	1.9	1.9	0.9
Lack of fit	15	40.0	2.7	1.2
System*Date	2	0.7	0.4	0.2
P Level*System*Date	17	13.5	0.8	0.4
Error	46	102.3	2.2	

Appendix 8.2.2. Analysis of variance of maize Leaf punch (% P) across different days after planting at Poamoho 1988.

Source of variation	df	SS*1000	MSS	F ratio
Corrected Total	114	2174.4		
Phosphorus Level	9	824.0	91.6	61.0 *
Log(P)	1	772.5	772.5	515.0 *
Log(P)*Log(P)	1	23.3	23.3	15.5 *
Lack of fit	7	28.2	4.0	2.7
System	2	7.5	3.8	2.5
P Level*System	14	41.2	2.9	2.0
Log(P)*SVI	1	3.6	3.6	2.4
Log(P)*INVIN	1	8.4	8.4	5.6
Lack of fit	12	29.2	2.4	1.6
Rep(P Level*System)	8	11.8	1.5	
Date	3	475.5	158.5	21.7 *
Date (linear)	1	353.1	353.1	48.4 *
Date*Date	1	114.0	114.0	15.6 *
Lack of fit	1	8.4	8.4	1.2
Rep(Date)	3	51.9	17.3	
P Level*Date	27	642.1	23.8	15.9 *
Log(P)*Date	1	457.8	457.8	305.2 *
Log(P)*Log(P)*Date	1	4.5	4.5	3.0
Log(P)*Date*Date	1	138.5	138.5	92.3 *
Lack of fit	24	41.3	1.7	1.1
System*Date	6	2.8	0.5	0.3
SVI*Date	1	0.4	0.4	0.3
INVIN*Date	1	0.1	0.1	0.1
P Level*System*Date	42	117.5	2.8	1.9
Error	53	77.5	1.5	

Appendix 8.2.3. Analysis of variance of maize Leaf punch (% P) across different days after planting at Poamoho 1989.

Source of variation	df	SS*1000	MSS	F ratio
Corrected Total	142	579.0		
Phosphorus Level	9	147.5	16.4	20.7 *
Log(P)	1	127.2	127.2	161.0 *
Log(P)*Log(P)	1	0.2	0.2	0.3
Lack of fit	7	20.1	2.9	3.6
System	1	5.0	5.0	6.3 *
P Level*System	9	12.3	1.4	1.7
Log(P)*System	1	5.8	5.8	7.3 *
Lack of fit	8	6.5	0.8	1.0
Rep(P Level)*System)	8	6.3	0.8	
Date	3	167.7	55.9	6.6
Date (linear)	1	135.8	135.8	16.0 *
Date*Date	1	1.5	1.5	0.2
Lack of fit	1	30.4	30.4	3.6
Rep(Date)	3	25.4	8.5	
P Level*Date	27	107.3	4.0	3.3 *
Log(P)*Date	1	17.0	17.0	14.2 *
Log(P)*Log(P)*Date	1	14.5	14.5	12.1 *
Log(P)*Date*Date	1	39.4	39.4	32.8 *
Lack of fit	24	36.4	1.5	1.3
System*Date	3	3.7	1.2	1.0
P Level*System*Date	27	39.8	1.5	1.2
Error	52	63.9	1.2	

Appendix 9.1. Analysis of variance of stover and grain phosphorus concentration at harvest.

(a) Soybean stover (P%):

Source of variation	df	SS*1000	MSS*1000	F ratio
Corrected Total		59		
Environments(Env)	1	15.1	15.1	13.0 **
Phosphorus Level	9	477.5	53.1	45.6 **
Log(P)	1	415.4	415.4	357.3 **
Log(P)*Log(P)	1	23.8	23.8	20.5 **
Lack of fit	7	38.3	5.5	4.7
Environment*P Level	9	68.5	7.6	6.5 *
Environment*Log(P)	1	60.0	60.0	51.6 **
Environment*Log(P*Log(P)	1	1.0	1.0	0.9
Lack of fit	7	7.5	1.1	0.9
Rep(Env*P Level)	8	9.3	1.2	
System	1	137.7	137.7	88.3 **
Environment*System	1	3.4	3.4	2.2
P Level*System	9	20.7	2.3	1.5
Env*P Level*System	5	39.5	7.9	5.1 **
Error	16	25.0	1.6	

(b) Soybean grain (P%):

Source of variation	df	SS*1000	MSS*1000	F ratio
Corrected Total	58			
Environment	1	105.6	105.6	5.8 *
Phosphorus Level	9	250.7	27.9	1.5
Log(P)	1	160.2	160.2	8.7 *
Log(P)*Log(P)	1	17.6	17.6	1.0
Lack of fit	7	72.9	10.4	0.6
Environment*P Level	9	69.9	7.8	0.4
Environment*Log(P)	1	14.0	14.0	0.8
Environment*Log(P)*Log(P)	1	17.0	17.0	0.9
Lack of fit	7	38.9	5.6	0.3
Rep(Env*P Level)	8	146.7	18.3	
System	1	51.7	51.7	4.6 *
Environment*System	1	82.5	82.5	7.3 *
P Level*System	9	116.7	13.0	1.1
Env*P Level*System	5	39.7	7.9	0.7
Error	15	169.9	11.3	

Appendix 9.2. Analysis of variance of maize P concentration plant stover and grain at harvest.

(a) Maize stover (P%):

Source of variation	df	SS*1000	MSS*1000	F ratio
Corrected Total	74			
Environment	1	7.3	7.3	4.2
Phosphorus Level	9	284.0	31.6	18.2 **
Log(P)	1	202.0	202.0	116.3 **
Log(P)*Log(P)	1	30.0	30.0	17.3 **
Lack of fit	7	52.0	7.4	4.3
Environment*P Level	8	47.0	5.9	3.4
Environment*Log(P)	1	0.7	0.7	0.4
Environment*Log(P)*Log(P)	1	19.0	19.0	10.9 *
Lack of fit	6	27.3	4.6	2.6
Rep(Env*P Level)	8	13.9	1.7	
System	2	2.6	1.3	0.1
Environment*System	1	0.8	0.8	0.0
P Level*System	17	41.0	2.4	0.1
Env*P Level*System	4	16.5	4.1	0.2
Error	24	443.1	18.5	

(B) Maize grain (P%):

Source of variation	df	SS*1000	MSS*1000	F ratio
Corrected Total	77			
Environment	1	370.0	370.0	274.1 **
Phosphorus Levels	9	26.5	2.9	2.2
Log(P)	1	7.9	7.9	5.9 *
Log(P)*Log(P)	1	5.6	5.6	4.1
Lack of fit	7	13.0	1.9	1.4
Environment*P Level	9	79.0	8.8	6.5 *
Environment*Log(P)	1	63.0	63.0	46.7 **
lack of fit	8	16.0	2.0	1.5
Rep(Env*P Level)	8	10.8	1.4	
System	2	3.9	2.0	1.2
Environment*System	1	0.8	0.8	0.5
P Level*System	18	16.0	0.9	0.6
Env*P Level*System	5	2.9	0.6	0.4
Error	24	38.7	1.6	

Appendix 9.3. Analysis of variance of P uptake at Poamoho during 1988 and 1989.

(a) Soybean

Source of variation	df	SS	MSS	F ratio
Corrected Total	58			
Environment	1	765.4	765.4	27.5**
Phosphorus Level	9	2809.8	312.2	11.2**
Log(P)	1	2192.2	2192.2	78.9**
Log(P)*Log(P)	1	164.8	164.8	5.9**
Lack of fit	7	452.8	64.7	2.3
Environment*P Level	9	704.1	78.2	2.8
Environment*Log(P)	1	534.7	534.7	19.2**
Lack of fit	8	169.4	21.2	0.8
Rep(Env*P Level)	8	222.2	27.8	
System	1	2557.7	2557.7	175.2**
Environment*System	1	62.8	62.8	4.3
P Level*System	9	538.5	59.8	4.1
Log(P)* System	1	315.9	315.9	21.6**
Lack of fit	8	222.6	27.8	1.9
Env*P Level*System	5	274.6	54.9	3.8
Error	15	219.3	14.6	

(b) Maize

Source of variation	df	SS	MSS	F ratio
Corrected Total	72			
Environment	1	9341.3	9341.3	241.4 **
Phosphorus Level	9	5734.6	637.2	16.5 **
Log(P)	1	4115.7	4115.7	106.3 **
Log(P)*Log(P)	1	910.3	910.3	23.5 **
Lack of fit	7	708.6	101.2	2.6
Environment*P Level	7	3690.9	527.3	13.6 **
Environment*Log(P)	1	935.7	935.7	24.2 **
Environment*Log(P)*Log(P)	1	1115.5	1115.5	28.7 **
Lack of fit	5	1639.7	327.9	8.5 *
Rep(Env*P Level)	8	309.3	38.7	
System	2	49.5	24.9	1.4
Environment*System	1	26.0	26.0	1.5
P Level*System	16	531.0	33.2	1.9
Env*P Level*System	4	108.4	27.1	1.5
Error	24	428.2	17.8	

Appendix 10.1. Analysis of variance of root dry weight (mg/100 cm^3 soil) at surface and subsurface layers at Poamoho 1988.

(a) 0 - 0.15 m layer

Sources of variation	df		SS	MSS	F ratio
Corrected Total	51				
Phosphorus Level	9		340.0	37.8	0.57
Log(P)		1	1.2	1.2	0.02
Log(P)*Log(P)		1	47.1	47.1	0.71
Lack of fit		7	291.7	41.7	0.62
System	4		4499.5	1124.9	16.86 **
P Level*System	22		3929.5	178.6	2.68 *
Error	16		1067.5	66.7	(CV=14.4%)

(b) 0.15 - 0.40 m layer

Sources of variation	df		SS	MSS	F ratio
Corrected Total	51				
Phosphorus Level	9		1009.2	112.1	0.86
Log(P)		1	2.3	2.3	0.02
Log(P)*Log(P)		1	99.2	99.2	0.76
Lack of fit		7	907.8	129.7	1.00
System	4		606.0	151.5	1.16
P Level*System	22		1523.5	69.3	0.53
Error	16		2085.1	130.3	(CV=37.9%)

(c) 0 - 0.40 m layer

Sources of variation	df		SS	MSS	F ratio
Corrected Total	51				
Phosphorus Level	9		457.3	50.8	0.68
Log(P)		1	1.8	1.8	0.02
Log(P)*Log(P)		1	77.4	77.4	1.03
Lack of fit		7	378.1	54.0	0.72
System	4		1537.1	384.3	5.14 **
P Level*System	22		1618.7	73.6	0.98
Error	16		1197.4	74.8	(CV=21.6%)

Appendix 10.2. Analysis of variance of root dry weight ($mg/100cm^3$ soil) at surface and subsurface layers at Poamoho 1989.

(a) 0 - 0.15 m layer

Sources of variation	df	SS	MSS	F ratio
Corrected Total	35			
Phosphorus Level	3	659.0	73.2	0.21
Log(P)	1	1.8	1.8	0.01
Log(P)*Log(P)	1	5.2	5.2	0.02
Lack of fit	1	651.9	651.9	1.87
System	2	1109.7	554.8	1.59
P Level*System	6	6313.7	1052.3	3.02 *
Error	24	8360.4	348.3	(CV=38.0%)

(b) 0.15 - 0.40 m layer

Sources of variation	df	SS	MSS	F ratio
Corrected Total	35			
Phosphorus Level	3	1271.1	141.2	0.69
Log(P)	1	368.1	368.1	1.79
Log(P)*Log(P)	1	888.4	888.4	4.32
Lack of fit	1	14.6	14.6	0.07
System	2	349.8	174.9	0.85
P Level*System	6	2880.2	480.0	2.34
Error	24	4930.3	205.4	(CV=52.1%)

(c) 0 - 0.40 m layer

Sources of variation	df	SS	MSS	F ratio
Corrected Total	35			
Phosphorus Level	3	587.5	195.8	1.20
Log(P)	1	156.1	156.1	0.96
Log(P)*Log(P)	1	379.7	379.7	2.33
Lack of fit	1	51.7	51.7	0.32
System	2	266.9	133.5	0.82
P Level*System	6	1695.7	282.6	1.73
Error	24	3915.3	163.1	(CV=34.5%)

Appendix 11.1. Main plots target P concentration in soil solution and the amount of P added based on P sorption isotherms to achieve the target P concentration in 1988 and 1989 at Poamoho.

	1988		1989	
Target P Conc.	P added	TSP/plot	P added	TSP/plot
(mg/L)	(mg/kg)	(g)	(mg/kg)	(g)
0.003	0	0	0	0
0.006	0	0	5	446
0.012	5	447	12	1070
0.025	12	1073	14	1249
0.05	8	715	22	1962
0.1	44	3935	15	1338
0.2	24	2146	0	0
0.4	35	3130	20	1784
0.8	50	4472	62	5530
1.6	53	4740	80	7136

Appendix 11.2

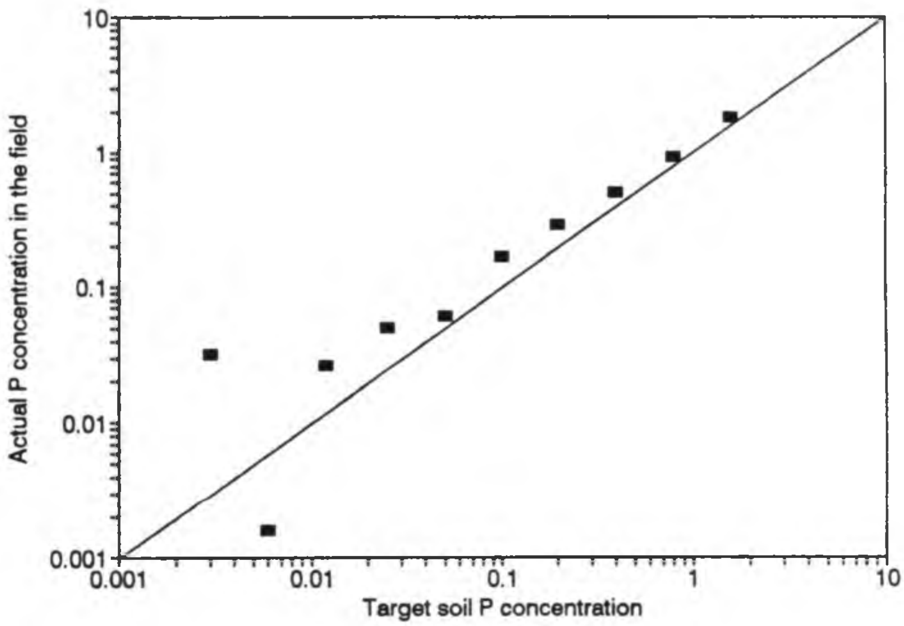

Figure 24. Actual and target soil solution P concentration on main plot treatments after fertilization.

Appendix 12.1a. Maize plant height (cm) at Kauai 1987 at different growth stages.

P Conc.	Rep	50 DAP		90 DAP		130 DAP	
		M	MS	M	MS	M	MS
(mg/L)							
0.003	3	132.7	89.3	104.0	140.0	101.7	136.3
0.006	2	95.3	94.3	147.7	149.0	138.3	149.7
0.012	3	94.3	92.3	151.0	136.0	147.3	130.3
0.012	1	108.7	104.3	156.3	143.3	151.7	133.3
0.025	3	80.3	101.0	126.0	117.0	128.7	123.7
0.025	2	121.3	115.3	137.3	141.3	161.0	120.0
0.025	1	96.3	110.3	148.0	148.0	151.3	126.0
0.05	3	109.0	112.3	153.3	147.7	157.0	141.7
0.05	2	106.3	111.7	153.3	138.0	156.3	146.0
0.05	1	72.3	113.3	161.0	117.7	144.0	127.3
0.1	3	130.7	135.0	142.3	131.3	144.0	143.7
0.1	2	118.0	98.7	147.3	151.3	136.7	103.0
0.1	1	116.7	120.3	150.0	151.0	160.7	174.0
0.2	3	119.7	114.0	152.7	151.3	173.3	142.3
0.2	2	125.0	145.3	156.0	148.7	168.0	128.7
0.2	1	116.0	136.7	128.0	156.3	101.3	113.0
0.4	3	131.7	123.0	135.7	141.7	162.7	146.0
0.4	1	102.3	109.0	124.7	135.7	130.0	130.3
0.8	2	135.0	127.0	149.7	144.3	138.3	157.3
1.6	3	127.3	106.0	113.0	147.0	125.3	145.3

Appendix 12.2a. Maize plant height (cm) at different growth stages at Poamoho 1988.

P Conc.	Rep	27 DAP			49 DAP			62 DAP			71 DAP		
		M	MS	MR	M	MS	MR	M	MS	MR	M	MS	MR
(mg/L)													
0.012	1	4.7	11.7	6.0	19.0	45.3	20.7	32.7	85.3	35.3	87.0	156.0	87.7
0.006	1		11.0	6.0		27.7	17.7		46.3	32.0		56.3	71.7
0.2	1		12.0	17.7		48.0	34.3		117.3	63.3		137.7	114.0
0.5	1		18.7	17.3		49.7	60.3		89.7	121.7		145.3	176.7
0.1	1		19.0	19.0		64.3	58.3		111.0	95.0		171.7	122.7
0.025	1	14.7	10.7	13.0	47.0	51.3	41.7	87.3	122.0	94.3	156.0	154.7	152.3
0.003	2	6.3	4.0	4.7	50.7	26.7	37.3	101.7	74.7	82.7	131.7	96.3	123.3
0.5	2	12.0	12.7	14.7	60.7	60.0	66.7	130.7	128.3	127.7	157.0	184.0	179.0
0.025	2		9.7	17.3		33.0	55.3		75.7	119.7		128.3	200.0
0.012	2		13.3	13.7		62.7	33.0		125.7	115.7		209.3	178.3
0.4	2	27.0	16.0	14.0	100.0	59.0	70.3	143.3	138.0	143.7	203.3	204.7	217.3
0.1	2	22.3	17.7	19.3	121.0	82.7	115.7	170.0	190.0	197.3	213.3	218.3	217.3
0.5	3		19.7	14.7		77.7	71.0		132.0	160.0		182.7	240.3
0.025	3		15.7	17.0		72.0	48.7		152.3	105.0		205.0	175.0
0.012	3		13.3	11.3		64.3	53.0		135.0	121.0		210.0	197.0
0.8	3		18.3	18.3		89.3	51.7		167.0	167.7		222.7	195.3
1.6	3		21.3	19.0		77.7	74.0		108.7	184.0		185.0	200.0
0.1	3		21.7	17.3		118.3	82.3		201.0	137.0		222.7	192.7

DAP: Days after planting, M: maize sole crop, MS: intercrop maize with soybean, and MR: intercrop maize with soybean.

Appendix 12.3a. Maize plant height (cm) at different growth stages at Poamoho 1989.

P Conc.	Rep	27 DAP M	27 DAP MS	50 DAP M	50 DAP MS	60 DAP M	60 DAP MS	70 DAP M	70 DAP MS	116 DAP M	116 DAP MS
(mg/L)											
0.012	1	58.3	53.3	124.7	114.3	215.0	200.0	261.7	260.7	238.3	246.7
0.006	1	37.3	46.0	100.7	116.7	198.3	235.0	254.7	255.0	248.3	236.7
0.2	1	57.7	61.0	151.0	146.3	241.7	250.0	243.7	230.0	241.7	250.0
0.5	1	55.0	55.7	141.7	165.0	214.3	248.3	255.7	275.0	251.7	229.7
0.1	1	59.0	59.3	150.7	142.7	240.0	243.3	240.7	265.0	256.7	245.0
0.025	1	57.0	52.3	146.0	144.3	260.0	251.7	268.3	259.0	275.0	263.3
0.003	2	37.3	37.7	85.0	89.0	156.7	156.7	232.3	254.3		
0.5	2	57.0	58.7	146.0	147.7	226.7	245.0	267.7	263.7	271.7	251.7
0.025	2	49.3	47.3	128.3	143.3	215.0	226.7	247.7	264.0	273.3	266.0
0.012	2	46.0	37.7	136.0	121.0	215.0	185.0	264.0	252.0	263.3	231.7
0.4	2	56.3	54.3	137.3	142.7	248.3	246.7	273.7	269.0	271.7	283.3
0.1	2	50.0	51.3	135.0	158.0	248.3	250.0	254.3	260.0	260.0	263.3
0.5	3	47.3	51.7	140.0	146.7	245.0	260.0	282.3	279.3	266.7	278.3
0.025	3	41.3	43.0	123.3	125.3	241.7	230.0	260.0	264.0	260.0	248.3
0.012	3	45.0	42.3	133.3	141.0	238.3	216.7	244.3	250.0	258.3	261.7
0.8	3	63.0	57.7	185.0	176.7	271.7	271.7	276.7	295.0	268.3	268.3
1.6	3	67.3	68.7	166.7	165.0	276.7	288.3	263.3	271.0		
0.1	3	57.0	54.3	148.7	160.0	256.7	256.7	281.7	271.7	228.3	260.0

Appendix 12.2b. Plant height (cm) of soybean at different growth stages at Poamoho 1988.

P Conc.	Rep	27 DAP S	27 DAP SM	49 DAP S	49 DAP SM	62 DAP S	62 DAP SM	71 DAP S	71 DAP SM
(mg/L)									
0.012	1		10.7		66.7		75.3		97.3
0.006	1		8.3		46.7		66.3		68.7
0.2	1	14.0	14.0	94.7	94.0	99.7	100.3	110.0	106.3
0.5	1		17.3		82.3		97.3		106.7
0.1	1	14.3	13.0	94.7	89.0	88.3	95.3	114.0	116.7
0.025	1		12.0		78.7		78.0		94.3
0.003	2		8.0		53.7		60.3		76.0
0.5	2		15.0		83.7		103.7		93.3
0.025	2	11.0	14.3	75.7	67.0	98.0	83.3	100.3	95.0
0.012	2	10.0	10.3	72.0	88.0	86.0	100.3	88.3	
0.4	2		15.0		101.0		96.0		110.0
0.1	2		15.3		88.3		96.7		104.7
0.5	3	18.0	12.3	94.3	90.3	102.7	87.0	105.0	110.0
0.025	3		21.3		81.3		95.7		100.0
0.012	3		13.0		78.7		94.7		94.3
0.8	3		15.7		95.0		104.3		104.7
1.6	3	12.0	14.7	96.0	94.0	102.3	88.0	103.3	107.7
0.1	3		17.3		98.3		117.3		114.0

S: sole crop soybean and SM: intercrop soybean with maize.

Appendix 12.3b. Soybean plant height (cm) at different growth stages at Poamoho 1989.

P Conc	Rep	27 DAP		50 DAP		60 DAP		70 DAP	
		S	SM	S	SM	S	SM	S	SM
(mg/L)									
0.012	1	19.0	20.0	40.0	44.0	58.3	56.7	45.7	58.3
0.006	1	19.3	21.7	46.0	55.0	53.3	58.3	56.7	62.0
0.2	1	20.7	24.7	46.7	65.0	61.7	68.3	62.0	64.7
0.5	1	20.0	22.3	53.3	61.7	56.7	70.0	57.0	72.0
0.1	1	20.3	46.0	60.0	64.0	70.0	78.3	58.3	57.3
0.025	1	21.0	23.0	56.7	63.3	65.0	71.7	60.7	65.0
0.003	2	15.7	19.0	39.3	50.0	50.0	60.0	54.3	67.0
0.5	2	22.3	23.7	65.0	66.7	61.7	66.7	64.0	65.0
0.025	2	21.3	18.7	45.3	61.7	55.0	68.3	55.0	63.7
0.012	2	17.3	20.7	41.7	55.0	46.7	71.7	53.0	64.0
0.4	2	20.0	25.7	53.3	65.0	63.3	71.7	62.7	63.0
0.1	2	19.3	25.0	52.3	71.7	61.7	75.0	54.3	66.7
0.5	3	23.0	23.0	55.0	63.3	63.3	75.0	60.7	78.3
0.025	3	22.0	23.7	61.7	65.0	66.7	75.0	59.7	73.7
0.012	3	20.3	22.3	53.3	63.3	60.0	78.3	62.0	73.3
0.8	3	21.7	27.3	58.3	68.3	66.7	80.0	67.7	64.3
1.6	3	29.0	25.0	75.0	55.0	78.3	51.7	70.3	59.3
0.1	3	22.7	23.3	61.7	63.3	66.7	66.7	59.3	67.3

Appendix 13a. Plant canopy (height and width in cm) measurement at different growth stages during the experiment planting on June 8, 1989 at Poamoho.

Date 7/5/89

		Sole crop maize						Intercrop maize					
P Conc.	Rep	height			width			Height			width		
		s1	s2	s3	s1	s2	s3	s1	s2	s3	s1	s2	s3
(mg/L)													
0.012	1	59	61	55	60	40	54	52	58	50	42	45	55
0.006	1	40	40	32	30	36	38	44	49	45	32	45	40
0.2	1	59	59	55	45	45	40	61	62	60	50	57	55
0.5	1	57	56	52	43	48	50	57	55	55	40	45	47
0.1	1	54	60	63	54	42	50	68	58	52	55	45	42
0.025	1	60	58	53	35	45	42	53	53	51	45	45	42
0.003	2	30	45	37	48	32	33	45	29	39	22	30	29
0.5	2	54	60	57	45	44	43	58	60	58	45	50	44
0.025	2	50	51	47	45	40	42	46	50	46	47	42	42
0.012	2	45	48	45	38	35	45	36	39	38	35	38	40
0.4	2	58	52	59	46	48	50	52	55	56	45	44	55
0.1	2	49	48	53	40	45	37	49	50	55	50	45	42
0.5	3	48	48	46	30	35	40	51	56	48	45	40	40
0.025	3	40	44	40	40	40	35	42	46	41	40	40	42
0.012	3	46	43	46	40	38	39	53	39	35	40	40	32
0.8	3	66	61	62	50	55	52	56	57	60	45	52	55
1.6	3	65	65	72	60	65	70	68	72	66	23	20	27
0.1	3	54	57	60	60	50	48	55	56	52	50	53	50

Date 7/27/89

P Conc.	Rep	height			width			Height			width		
		s1	s2	s3	s1	s2	s3	s1	s2	s3	s1	s2	s3
(mg/L)													
0.012	1	115	125	134	70	75	70	105	118	120	65	60	70
0.006	1	95	102	105	65	55	55	105	120	125	60	55	50
0.2	1	138	150	165	60	60	65	152	145	142	45	50	55
0.5	1	150	130	145	65	70	75	165	175	155	65	60	65
0.1	1	150	150	152	50	65	60	130	148	150	60	65	60
0.025	1	145	148	145	65	65	55	135	150	148	45	60	70
0.003	2	85	92	78	55	60	55	95	80	92	50	50	50
0.5	2	142	150	146	60	60	65	143	155	145	50	50	45
0.025	2	130	130	125	60	55	50	155	140	135	50	55	60
0.012	2	130	140	138	60	55	55	108	113	142	60	65	65
0.4	2	135	135	142	50	50	55	137	145	146	60	60	65
0.1	2	135	135	135	70	65	75	164	160	150	55	50	50
0.5	3	140	145	135	55	60	65	155	145	140	55	50	50
0.025	3	120	122	128	50	55	60	130	120	126	50	55	60
0.012	3	130	135	135	55	55	50	140	145	138	55	50	50
0.8	3	190	185	180	60	65	70	185	175	170	75	75	70
1.6	3	170	175	155	70	65	60	155	175	165	65	60	60
0.1	3	153	153	140	60	60	65	165	165	150	55	60	60

s1= sample one, s2= sample two and s3= sample three.

Date 8/14/89

P Conc.	Rep	Sole crop maize height s1	s2	s3	Sole crop maize width s1	s2	s3	Intercrop maize Height s1	s2	s3	Intercrop maize width s1	s2	s3
(mg/L)													
0.012	1	258	267	260		95		255	270	257		110	
0.006	1	260	239	265		100		265	242	258		120	
0.2	1	264	225	242		105		225	260	205		115	
0.5	1	266	251	250		100		265	280	280		80	
0.1	1	245	235	242		110		250	265	280		100	
0.025	1	268	275	262		115		260	270	247		125	
0.003	2	241	236	220		95		245	260	258		110	
0.5	2	280	252	271		100		251	275	265		105	
0.025	2	250	240	253		120		265	257	270		130	
0.012	2	285	263	244		105		261	250	245		120	
0.4	2	266	280	275		110		262	265	280		110	
0.1	2	290	240	233		115		270	280	230		135	
0.5	3	267	300	280		105		285	285	268		120	
0.025	3	240	260	280		105		270	280	242		120	
0.012	3	265	268	200		90		255	215	280		125	
0.8	3	270	280	280		135		290	295	300		120	
1.6	3	270	270	250		115		260	278	275		110	
0.1	3	295	280	270		125		290	260	265		120	

Appendix 13b. Soybean canopy measurement at Poamoho 1989 at different days after planting.
Date 7/5/89

P Conc.	Rep	Sole crop soybean height s1	s2	s3	Sole crop soybean width s1	s2	s3	Intercrop soybean Height s1	s2	s3	Intercrop soybean width s1	s2	s3
(mg/L)													
0.012	1	20	18	19	17	15	20	20	18	22	20	20	15
0.006	1	20	19	19	15	18	18	24	20	21	23	20	19
0.2	1	21	22	19	19	15	15	25	25	24	20	24	19
0.5	1	19	18	23	18	16	16	18	23	26	25	20	23
0.1	1	22	20	19	20	19	24	48	46	44	26	22	23
0.025	1	20	21	22	20	18	22	24	23	22	20	23	22
0.003	2	16	16	15	16	14	12	19	16	22	16	13	18
0.5	2	21	22	24	22	20	20	23	22	26	22	23	25
0.025	2	18	24	22	20	20	18	19	18	19	18	19	20
0.012	2	17	15	20	13	17	15	20	20	22	20	14	17
0.4	2	19	22	19	24	21	20	27	25	25	25	23	21
0.1	2	19	19	20	20	19	18	26	25	24	21	24	22
0.5	3	23	22	24	22	20	21	23	23	23	19	18	20
0.025	3	24	21	21	20	23	20	25	21	25	20	18	20
0.012	3	20	19	22	17	18	19	23	24	20	25	23	23
0.8	3	22	22	21	25	20	22	30	25	27	30	30	18
1.6	3	32	28	27	25	23	24	25	23	27			
0.1	3	21	23	24	20	22	20	23	24	23	20	19	22

2nd date 7/27/89

		Sole crop soybean						Intercrop soybean					
P Conc.	Rep	height			width			Height			width		
		s1	s2	s3	s1	s2	s3	s1	s2	s3	s1	s2	s3
(mg/L)													
0.012	1	35	45	40	35	30	30	45	42	45	40	35	35
0.006	1	48	45	45	35	35	45	60	50	55	40	35	30
0.2	1	55	45	40	40	50	55	65	65	65	40	45	40
0.5	1	45	60	55	45	40	50	60	65	60	50	40	35
0.1	1	65	55	60	55	40	50	65	65	62	50	50	40
0.025	1	60	55	55	50	45	50	65	60	65	35	40	45
0.003	2	38	40	40	40	50	35	40	50	60	40	45	45
0.5	2	55	65	75	55	60	50	65	70	65	50	45	50
0.025	2	45	46	45	40	42	42	60	65	60	45	40	45
0.012	2	40	45	40	45	35	40	50	55	60	35	40	40
0.4	2	55	55	50	45	50	45	70	65	60	40	45	50
0.1	2	55	50	52	50	45	55	65	75	75	45	45	35
0.5	3	50	55	60	60	50	50	55	65	70	40	45	40
0.025	3	60	65	60	45	55	55	65	70	60	45	45	40
0.012	3	55	60	45	45	50	50	70	65	55	60	65	55
0.8	3	55	60	60	60	50	55	65	75	65	50	45	40
1.6	3	80	70	75	65	60	65	60	50	55	45	50	40
0.1	3	60	60	65	60	55	50	60	65	65	35	35	40

4th date 8/14/89

		Sole crop soybean						Intercrop soybean					
P Conc.	Rep	height			width			Height			width		
		s1	s2	s3	s1	s2	s3	s1	s2	s3	s1	s2	s3
(mg/L)													
0.012	1	44	40	53		65		66	59	50		55	
0.006	1	55	58	57		80		61	68	57		65	
0.2	1	58	60	68		65		64	62	68		55	
0.5	1	62	58	51		60		67	84	65		70	
0.1	1	55	58	62		70		61	58	53		60	
0.025	1	63	59	60		65		67	61	67		80	
0.003	2	60	52	51		70		67	69	65		75	
0.5	2	70	65	57		70		77	58	60		65	
0.025	2	55	55	55		60		70	59	62		65	
0.012	2	51	55	53		75		66	54	72		60	
0.4	2	65	58	65		65		61	65	63		65	
0.1	2	55	57	51		70		70	65	65		75	
0.5	3	65	62	55		75		80	81	74		55	
0.025	3	65	57	57		80		63	79	79		60	
0.012	3	61	67	58		70		79	73	68		65	
0.8	3	70	65	68		75		62	63	68		60	
1.6	3	75	70	66		75		55	58	65		60	
0.1	3	64	55	59		80		70	63	69		60	

Appendix 14a. Maize growth stages at different days after planting at Poamoho 1988. Date of planting 5/17/1988

Date	DAP	P Conc.	Sole crop s1	Sole crop s2	Sole crop s3	Int./soybean s1	Int./soybean s2	Int./soybean s3	Int./rice s1	Int./rice s2	Int./rice s3
		(mg/L)									
5/20	3	0.003	VE								
		1.6	VE								
5/23	5	0.003	V2								
		1.6	V2								
5/31	14	0.003	V3								
		1.6	V3								
6/6	20	0.003	V5	V5	V4						
		1.6	V6	V6	V5						
6/8	22	0.003	V6	V6	V5						
		1.6	V6	V6	V6						
6/14	28	0.003	V6	V7	V6						
		1.6	V8	V8	V8						
6/17	31	0.003	V8	V7	V7						
		1.6	V8	V8	V8						
6/23	35	0.003	V10	V9	V9						
		1.6	V11	V11	V10						
6/29	41	0.003	V11	V11	V10						
		1.6	V13	V13	V12						
7/5	49	0.003	V13	V13	V13						
		1.6	V17	V15	V15						
		P Conc.	Sole crop			Int./soybean			Int./rice		
7/18	61	0.012	V12	V13	V12	V17	V14	V17	V14	V14	V13
		0.006				V15	V13	V15	V12	V14	V15
		0.2				V16	V17	V18	V15	V16	V17
		0.5				V18	V15	V15	V19	V20	V20
		0.1				V18	V18	V16	V16	V17	VT
		0.025	V16	V16	V16	V19	VT	V17	V18	V18	V17
		0.003	V18	V17	V17	V15	V17	V15	V17	V16	V17
		0.5	V18	V21	V21	V18	V20	V21	V21	V20	V19
		0.025				V15	V16	V16	V19	V19	V19
		0.012				V18	V18	V19	V19	V19	V20
		0.4	VT	VT	V20	V18	V19	V22	V19	VT	V20
		0.1	VT	VT	VT	VT	R1	VT	VT	R1	R1
		0.5				VT	VT	V18	V19	V20	V21
		0.025				V21	V21	VT	V18	V19	VT
		0.012				V21	V21	V21	V21	V19	V22
		0.8				V21	V21	VT	VT	VT	R1
		1.6				V20	V20	V18	R1	VT	VT
		0.1				VT	VT	R1	V19	V20	VT
7/21	64	0.012	V13	V13	V14	V18	V17	V18	V15	V16	V17
		0.006				V14	V13	V15	V14	V16	V15
		0.2				VT	V20	V21	VT	V20	V21
		0.5				VT	V20	V21	VT	VT	V21
		0.1									
		0.025	VT	VT	V22	VT	VT	VT	VT	VT	VT
		0.003	V18	V18	V19	V16	V15	V15	V16	V15	V17
		0.5	VT	VT	VT	VT	VT	VT	VT	VT	VT
		0.025				V15	V20	V21	VT	VT	R1
		0.012				V19	V20	V22	VT	V20	V21
		0.4	VT	R1	R1	VT	VT	R1	VT	VT	R1
		0.1	R1	R1	R1	VT	VT	R1	VT	R1	R1
		0.5				VT	R1	VT	VT	VT	R1
		0.025				VT	VT	VT	VT	V20	V21
		0.012				VT	V21	V22	VT	V19	V20
		0.8				VT	VT	R1	VT	VT	V22
		1.6				VT	R1	VT	VT	VT	R1
		0.1				VT	R1	R1	VT	VT	V21

Date	DAP	P Conc.	Sole crop s1	Sole crop s2	Sole crop s3	Int./soybean s1	Int./soybean s2	Int./soybean s3	Int./rice s1	Int./rice s2	Int./rice s3
		(mg/L)									
7/27	70	0.012	VT	V18	V19	VT	VT	VT	VT	V18	VT
		0.006				V19	V20	V21	V21	V21	V20
		0.2				VT	R1	R1	VT	VT	R1
		0.5				R1	VT	VT	R1	R1	VT
		0.1				R1	R1	R1	R1	R1	R1
		0.025	VT	R1	R1	R1	R1	R1	R1	VT	VT
		0.003	VT	VT	VT	VT	V17	V18	VT	VT	V19
		0.5	R1	R1	R1	R1	R1	R1	R1	R1	R1
		0.025				VT	VT	VT	R1	R1	R1
		0.012				R1	R1	VT	R1	R1	VT
		0.4	R	R	R	R	R	R	R1	R1	R1
		0.1	R1	R1	R1	R1	R1	R1	R1	R1	R1
		0.5				R1	R1	R1	R1	R1	R1
		0.025				R1	R1	R1	R1	R1	R1
		0.012				R1	R1	R1	R1	R1	VT
		0.8				R1	R1	R1	R1	R1	R1
		1.6									
		0.1									
8/2	76	0.012	R1	R1	R1	R2	R2	R1	R1	R1	R2
		0.006				VT	VT	R1	VT	VT	R1
		0.2				R2	R2	R2	R2	R2	R2
		0.5				R1	R1	R2	R1	R1	R2
		0.1				R2	R2	R2	R2	R2	R2
		0.025	R1	R1	R2	R1	R1	R2	R1	R1	R2
		0.003	R1	R1	R1	R1	R1	R1	R1	R1	R1
		0.5	R2	R2	R2	R2	R2	R2	R2	R2	R2
		0.025				R1	R1	R1	R2	R2	R2
		0.012				R2	R2	R1	R1	R1	R2
		0.4	R3	R2	R2	R3	R2	R2	R3	R2	R2
		0.1	R2	R2	R3	R2	R2	R3	R2	R2	R3
		0.5				R2	R2	R2	R2	R2	R2
		0.025				R2	R2	R1	R1	R1	R2
		0.012				R2	R2	R1	R1	R1	R1
		0.8				R2	R2	R2	R2	R2	R2
		1.6				R2	R2	R2	R2	R2	R2
		0.1				R2	R2	R2	R2	R2	R1
8/11	85	0.012	R2	R2	R2	R2	R2	R2	R2	R2	R2
		0.006				R2	R2	R2	R2	R2	R2
		0.2				R4	R3	R3	R4	R3	R3
		0.5				R4	R4	R3	R4	R4	R3
		0.1				R3	R3	R4	R3	R3	R4
		0.025	R3	R3	R3	R3	R3	R4	R3	R3	R3
		0.003	R3	R3	R3	R2	R2	R2	R3	R2	R2
		0.5	R4	R4	R4	R4	R4	R4	R4	R4	R4
		0.025				R4	R4	R3	R4	R4	R4
		0.012				R3	R3	R3	R3	R3	R2
		0.4	R3	R4	R4	R4	R4	R4	R4	R4	R4
		0.1	R4	R4	R4	R4	R4	R4	R4	R4	R4
		0.5				R4	R4	R4	R4	R4	R4
		0.025				R3	R3	R4	R3	R3	R2
		0.012				R3	R3	R3	R3	R3	R2
		0.8				R4	R4	R4	R4	R4	R3
		1.6				R4	R4	R4	R4	R4	R4
		0.1				R4	R4	R4	R4	R4	R4

Appendix 14b. Soybean growth stages at different during the experiment at Poamoho 1988.

Date	DAP	P Conc. (mg/L)	Sole Soybean s1	Sole Soybean s2	Sole Soybean s3	Intercrop soybean s1	Intercrop soybean s2	Intercrop soybean s3
7/18	61	0.012				R5	R4	R5
		0.006				R4	R5	R5
		0.2	R5	R5	R5	R5	R5	R5
		0.5				R5	R5	R5
		0.1	R5	R5	R5	R5	R5	R5
		0.025				R5	R5	R5
		0.003				R5	R5	R5
		0.5				R5	R5	R5
		0.025	R5	R5	R5	R5	R5	R5
		0.012	R5	R5	R5	R5	R5	R5
		0.4				R5	R5	R5
		0.1				R5	R5	R5
		0.5	R5	R5	R5	R5	R5	R5
		0.025				R5	R5	R5
		0.012				R5	R5	R5
		0.8				R5	R5	R5
		1.6	R5	R5	R5	R5	R5	R5
		0.1				R5	R5	R5
8/2	76	0.012	R6	R6	R6	R6	R6	R6
		0.006	R6	R6	R6	R6	R6	R6
		0.2	R6	R6	R6	R6	R6	R6
		0.5	R6	R6	R6	R6	R6	R6
		0.1	R6	R6	R6	R6	R6	R6
		0.025	R6	R6	R6	R6	R6	R6
		0.003	R6	R6	R6	R6	R6	R6
		0.5	R6	R6	R6	R6	R6	R6
		0.025	R6	R6	R6	R6	R6	R6
		0.012	R6	R6	R6	R6	R6	R6
		0.4	R6	R6	R6	R6	R6	R6
		0.1	R6	R6	R6	R6	R6	R6
		0.5	R6	R6	R6	R6	R6	R6
		0.025	R6	R6	R6	R6	R6	R6
		0.012	R6	R6	R6	R6	R6	R6
		0.8	R6	R6	R6	R6	R6	R6
		1.6	R6	R6	R6	R6	R6	R6
		0.1	R6	R6	R6	R6	R6	R6

Appendix 14c. Maize and soybean growth stages at different days after planting at Poamoho 1989.
(Date of planting 6/8/1991)

Date	P Conc.	Sole crop s1	Sole crop s2	Sole crop s3	Int. Maize s1	Int. Maize s2	Int. Maize s3	Sole crop s1	Sole crop s2	Sole crop s3	Intercrop s1	Intercrop s2	Intercrop s3
	(mg/L)												
6/18	0.025	V2	V3	V3	V3	V2	V3						
	0.003	V3	V2	V2	V3	V2	V2						
	1.6	V2	V2	V3	V3	V3	V2						
	0.1	V3	V3	V3	V2	V3	V3						
6/26	0.003	V4	V4	V4	V4	V4	V4	V1	V1	V1	V1	V1	V1
	1.6	V5	V5	V5	V5	V5	V5	V1	V1	V1	V1	V1	V1
	0.1	V5	V5	V5	V5	V5	V5	V1	V1	V1	V1	V1	V1
7/5	0.003	V7	V6	V6	V6	V6	V6	V3	V3	V3	V3	V3	V3
	1.6	V7	V8	V8	V8	V8	V8	V3	V3	V3	V3	V3	V3
	0.1	V8	V8	V8	V8	V8	V8	V3	V3	V3	V3	V3	V3
7/17	0.003	V10	V10	V10	V9	V9	V9	V6	V6	V6	V6	V6	V6
	1.6	V11	V12	V12	V13	V12	V12	V7	V7	V7	V7	V7	V7
	0.1	V12	V12	V12	V12	V12	V12	V7	V7	V7	V7	V7	V7

Date	P Conc.	Sole crop s1	Sole crop s2	Sole crop s3	Int. Maize s1	Int. Maize s2	Int. Maize s3	Sole crop s1	Sole crop s2	Sole crop s3	Intercrop s1	Intercrop s2	Intercrop s3
7/27	(mg/L)												
	0.012	V16	V15	V15	R1	R1	R1	V15	V16	V16	R1	R1	R1
	0.006	V14	V14	V14	R1	R1	R1	V15	V14	V14	R1	R1	R1
	0.2	V16	V15	V15	R1	R1	R1	V17	V17	V16	R1	R1	R1
	0.5	V15	V16	V17	R1	R1	R1	V17	V18	V17	R1	R1	R1
	0.1	V15	V16	V16	R1	R1	R1	V16	V15	V16	R1	R1	R1
	0.025	V17	V17	V17	R1	R1	R1	V15	V16	V16	R1	R1	R1
	0.003	V14	V14	V13	R1	R1	R1	V13	V12	V12	R1	R1	R1
	0.5	V16	V16	V15	R1	R1	R1	V15	V16	V17	R1	R1	R1
	0.025	V17	V17	V16	R1	R1	R1	V16	V16	V16	R1	R1	R1
	0.012	V15	V15	V15	R1	R1	R1	V15	V15	V15	R1	R1	R1
	0.4	V17	V16	V16	R1	R1	R1	V15	V16	V16	R1	R1	R1
	0.1	V16	V15	V16	R1	R1	R1	V18	V19	V17	R1	R1	R1
	0.5	V17	V17	V17	R1	R1	R1	V18	V17	V17	R1	R1	R1
	0.025	V15	V16	V15	R1	R1	R1	V13	V16	V16	R1	R1	R1
	0.012	V14	V17	V16	R1	R1	R1	V16	V15	V15	R1	R1	R1
	0.8	V19	V18	V19	R1	R1	R1	V18	V19	V18	R1	R1	R1
	1.6	V16	V17	V17	R1	R1	R1	V17	V18	V18	R1	R1	R1
	0.1	V17	V17	V16	R1	R1	R1	V16	V16	V16	R1	R1	R1

Appendix 15. Climatic data in three environments during the experiment.

Kauai 87/88						Poamoho 88						Poamoho 89					
Julian		Rain (")		Temp.C		Julian		Rain	Temp.C		Solar	Julian		Rain	Temp.C		Solar
Date	Date	Site 1	Site 2	Max	Min	Date	Date	(")	Max	Min	Rad	Date	Date	(")	Max	Min	Rad
305	Nov. 1	0.22		25	20	121	May 1	0.01	26.7	22.8	976	152	June 1	0.32	26.1	21.1	128
306	2	1.12	1.48	20	20	122	2	0.00	27.2	21.7	777	153	2	0.12	25.6	21.1	221
307	3	0.26	0.25	25	20	123	3	0.00	27.2	21.1	720	154	3	T	28.9	20.0	175
308	4	1.75	2.08	25	19	124	4	0.19	26.7	21.1	415	155	4	T	28.9	20.6	207
309	5	3.35	3.72	25	19	125	5	0.09	24.4	18.3	290	156	5	0.00	27.2	21.1	96
310	6	0.52	0.48	25	21	126	6	0.03	26.1	20.6	598	157	6	0.00	26.7	21.7	173
311	7	0.65		25	17	127	7	0.26	25.0	20.0	488	158	7	0.00	27.2	21.1	131
312	8	T		24	16	128	8	T	27.2	19.4	1026	159	* 8	0.00	26.7	20.6	45
313	9	T	0.08	25	17	129	9	0.00	27.2	20.0	1283	160	9	0.00	27.2	20.6	71
314	10	T	T	25	17	130	10	0.02	26.7	20.0	1243	161	10	0.00	28.9	20.6	92
315	11	0.65		26	17	131	11	0.07	23.3	18.9	763	162	11	0.00	27.2	21.1	109
316	12	0.08	0.79	26	21	132	12	0.06	22.8	19.4	476	163	12	0.00	27.8	21.1	82
317	13	0.16	0.28	26	20	133	13	0.12	25.0	20.0	565	164	13	0.00	27.8	21.7	92
318	14	0.00	0.00	25	19	134	14	0.21	24.4	20.0	515	165	14	0.00	28.9	20.0	60
319	15	0.07		26	17	135	15	0.07	25.0	20.6	720	166	15	0.00	27.2	19.4	99
320	16	0.00	0.20	22	17	136	16	0.02	26.1	20.0	941	167	16	0.00	28.3	21.1	89
321	* 17	0.00	0.00	24	17	137	* 17	0.01	11.1	20.0	1081	168	17	T	28.9	22.2	113
322	18	0.05	0.07	23	17	138	18	0.00	28.9	21.7	1046	169	18	0.03	26.7	21.1	113
323	19	0.16	0.20	23	17	139	19	0.00	28.3	21.7	1139	170	19	0.02	27.8	21.1	115
324	20	0.17	0.18	23	17	140	20	0.00	30.0	22.2	1217	171	20	0.00	28.3	21.1	39
325	21	1.60		23	19	141	21	0.00	27.8	20.6	1091	172	21	T	27.8	20.6	116
326	22	0.27		24	19	142	22	0.07	27.8	20.0	1182	173	22	0.01	27.8	21.1	106
327	23	0.08	2.51	24	19	143	23	0.05	27.2	20.6	1202	174	23	0.00	26.7	19.4	164
328	24	0.48	0.42	24	20	144	24	0.05	26.7	21.1	874	175	24	0.00	28.3	21.1	123
329	25	0.30	0.40	24	19	145	25	0.02	27.8	20.0	1057	176	25	0.00	28.9	21.1	90
330	26	0.31		24	19	146	26	0.07	26.7	19.4	1013	177	26	0.00	27.8	21.7	116
331	27	0.20	0.66	23	19	147	27	0.00	27.8	19.4	958	178	27	T	27.8	21.1	158
332	28	0.07		24	19	148	28	0.01	27.8	20.0	1300	179	28	0.00	28.3	21.1	61
333	29	0.15		22	19	149	29	0.02	27.2	19.4	950	180	29	0.00	28.3	22.2	83
334	30	0.00	0.24	23	19	150	30	0.00	27.8	21.1	1226	181	30	0.00	27.8	21.1	87
335	Dec. 1	0.00	0.00	24	18	151	31	0.02	27.8	19.4	1044	182	July 1	0.02	28.3	20.0	
336	2	0.00	0.00	24	19	152	June 1	0.00	28.3	21.7	1137	183	2	0.00	29.4	20.6	
337	3	0.00	0.00	24	19	153	2	0.02	26.7	21.1	524	184	3	0.00	28.9	21.1	
338	4	0.00	0.00	24	20	154	3	0.00	26.7	21.1	551	185	4	0.02	29.4	20.6	
339	5	0.00	0.00	24	17	155	4	0.00	28.9	21.1	1352	186	5	0.06	28.3	21.1	
340	6	0.00	0.00	23	17	156	5	0.04	26.7	21.1	710	187	6	0.02	29.4	22.2	
341	7	0.00	0.04	23	19	157	6	0.10	27.2	21.1	842	188	7	0.00	28.3	21.7	
342	8	0.00	0.00	24	17	158	7	0.06	27.8	21.1	987	189	8	0.00	28.9	20.6	
343	9	0.00	0.00	24	17	159	8	0.00	27.2	19.4	828	190	9	0.00	30.0	20.6	
344	10	0.07	0.09	25	17	160	9	0.00	27.2	20.0	969	191	10	0.02	29.4	21.1	
345	11	0.25	0.75	24	17	161	10	0.01	27.2	20.0	1007	192	11	0.01	27.2	22.2	
346	12	2.80		25	16	162	11	0.00	28.9	20.6	1211	193	12	0.00	28.3	21.7	
347	13	2.75		23	17	163	12	0.00	28.9	20.0	1262	194	13	0.00	27.8	22.2	
348	14	2.10	9.20	22	17	164	13	0.00	30.0	20.0	1223	195	14	T	27.8	21.7	
349	15	0.40	0.60	25	18	165	14	0.00	28.3	20.6	1230	196	15	T	28.3	22.8	
350	16	2.90	2.94	25	17	166	15	0.01	28.3	20.0	1247	197	16	0.00	30.0	22.2	
351	17	1.60	1.20	25	18	167	16	0.01	26.1	18.9	813	198	17	0.00	29.4	22.2	
352	18	3.70	3.90	25	18	168	17	0.00	28.3	20.0	1127	199	18	0.00	27.8	21.7	
353	19					169	18	0.00	30.0	20.0	1367	200	19	0.01	28.3	22.2	
354	20					170	19	0.00	28.9	18.9	1357	201	20	0.03	28.3	21.7	
355	21	0.75	0.76	25	17	171	20	0.02	27.8	21.1	1125	202	21	1.32	25.6	21.7	
356	22	0.10	0.05	25	17	172	21	T	26.7	21.7	765	203	22	0.51	25.6	22.8	
357	23	0.10	0.04	25	17	173	22	0.07	26.7	21.1	725	204	23	0.19	25.6	23.3	
358	24	0.15	0.17	25	18	174	23	0.00	30.0	21.7	1228	205	24	0.01	28.3	21.7	
359	25					175	24	0.05	27.2	21.1	854	206	25	0.01	28.3	21.1	946
360	26					176	25	0.00	28.9	21.1	1315	207	26	0.00	27.8	20.6	932
361	27					177	26	0.01	27.8	21.1	973	208	27	0.00	28.9	21.1	984
362	28	0.66	0.83	25	16	178	27	0.01	28.3	20.6	1156	209	28	0.03	29.4	21.7	480
363	29	0.07	0.05	25	16	179	28	0.00	27.8	21.7	1115	210	29	0.00	27.8	21.1	814
364	30	1.18	1.53	25	16	180	29	0.00	28.9	21.7	1034	211	30	T	27.8	20.6	714
365	31	0.66	0.72	22	16	181	30	0.00	28.9	22.2	1233	212	31	T	28.3	20.6	1103

Climatic data in three environments during the experiment.

Kauai 87/88 Julian Date	Date	Rain (") Site 1	Rain (") Site 2	Temp.C Max	Temp.C Min	Poamoho 88 Julian Date	Date	Rain (")	Temp.C Max	Temp.C Min	Solar Rad	Poamoho 89 Julian Date	Date	Rain (")	Temp.C Max	Temp.C Min	Solar Rad
1	Jan. 1					182	July 1	0.00	28.9	20.6	1101	213	Aug. 1	T	27.2	20.6	616
2	2					183	2	0.00	29.4	20.6	1133	214	2	0.05	27.2	21.1	672
3	3					184	3	0.00	28.9	20.6	1198	215	3	0.25	25.0	20.0	481
4	4	3.31	3.53	20	14	185	4	0.00	28.9	20.6	1151	216	4	0.01	27.8	21.1	962
5	5	0.00	0.00	27	14	186	5	0.00	27.8	21.7	757	217	5	0.00	28.9	21.1	967
6	6	0.00	0.01	21	15	187	6	0.00	28.9	21.1	1220	218	6	0.04	28.9	21.1	771
7	7	0.00	0.00	23	15	188	7	0.05	28.3	21.1	862	219	7	T	29.4	21.7	1154
8	8	0.00	0.00	23	15	189	8	0.20	27.2	21.7	819	220	8	0.25	27.2	22.2	497
9	9	0.00		23	16	190	9	0.07	28.3	21.7	1175	221	9	0.00	28.3	22.2	673
10	10	0.00		23	17	191	10	0.07	27.8	21.7	1068	222	10	0.00	28.9	21.1	883
11	11	0.21	0.30	22	18	192	11	0.01	28.3	21.7	1075	223	11	0.00	30.6	21.7	999
12	12	0.04	0.02	25	19	193	12	0.03	27.8	22.8	794	224	12	0.00	30.6	22.2	1094
13	13	0.00	0.01	25	16	194	13	T	27.2	21.7	804	225	13	0.08	30.0	21.1	708
14	14	0.00	0.00	25	15	195	14	0.09	28.9	21.7	1236	226	14	0.00	28.9	21.7	654
15	15	0.00	0.00	25	18	196	15	0.00	29.4	20.6	1149	227	15	0.00	28.9	22.2	962
16	16	0.16		24	18	197	16	0.00	28.3	22.2	1203	228	16	0.00	30.0	21.7	924
17	17	0.28		22	18	198	17	0.00	29.4	22.2	1128	229	17	0.00	28.9	21.1	899
18	18	0.00	0.41	26	16	199	18	0.00	30.0	21.1	1135	230	18	0.01	27.8	20.6	641
19	19	0.00	0.00	25	19	200	19	0.00	28.9	21.1	1303	231	19	0.04	26.7	21.1	528
20	20	0.00	0.00	24	14	201	20	T	29.4	21.1	1400	232	20	0.01	27.2	21.7	631
21	21	0.00	0.00	25	16	202	21	0.00	28.9	20.6	1302	233	21	0.23	27.2	22.8	494
22	22	0.00	0.00	25	16	203	22	0.00	28.9	21.1	1196	234	22	0.01	27.8	21.1	575
23	23	0.05		24	17	204	23	0.00	28.9	21.7	697	235	23	0.00	28.9	21.1	881
24	24	1.40		22	17	205	24	0.00	28.9	20.0	694	236	24	0.00	28.9	21.1	857
25	25	0.56	2.39	19	16	206	25	0.03	27.2	20.0	617	237	25	0.00	28.9	21.1	1067
26	26	0.02	0.04	20	15	207	26	0.19	27.8	20.6	578	238	26	0.00	28.9	21.1	816
27	27	0.07	0.10	19	15	208	27	0.01	28.9	22.2	1006	239	27	0.00	30.6	20.6	1101
28	28	0.94	1.28	26	16	209	28	0.00	28.9	21.1	1027	240	28	0.01	30.0	20.6	486
29	29	5.20	4.05	19	15	210	29	0.00	28.3	20.0	796	241	29	0.03	28.3	20.6	539
30	30	0.69		21	13	211	30	0.00	29.4	20.6	1393	242	30	0.00	28.9	21.1	877
31	31	0.03		24	14	212	31	0.00	28.9	22.8	1182	243	31	0.00	29.4	21.7	803
32	Feb. 1	0.00	0.62	23	15	213	Aug. 1	0.00	29.4	20.6	1310	244	Sept 1	0.01	29.4	27.8	961
33	2	0.00	0.00	24	15	214	2	0.00	29.4	21.7	1301	245	2	0.01	28.9	21.1	900
34	3	0.00	0.00	25	15	215	3	0.62	30.6	22.2	1032	246	3	0.02	27.8	21.1	635
35	4	0.05	0.17	24	15	216	4	0.01	30.0	21.1	1268	247	4	0.01	27.2	21.1	699
36	5	0.03	0.12	22	16	217	5	T	28.3	22.2	761	248	5	0.01	27.8	20.6	1041
37	6			24	14	218	6	0.00	28.3	21.1	1106	249	6	0.00	29.4	21.1	983
38	7			25	16	219	7	0.00	28.9	21.7	1280	250	7	0.08	28.9	22.2	612
39	8	0.24	0.19	24	17	220	8	0.00	28.9	23.3	904	251	8	0.01	29.4	21.1	1053
40	9	0.26	0.17	23	17	221	9	0.00	29.4	22.2	762	252	9	0.00	28.3	21.1	781
41	10	0.03	0.08	24	17	222	10	0.00	30.0	21.1	1100	253	10	T	28.3	20.6	907
42	11	0.23	0.28	24	18	223	11	1.13	28.3	22.8	939	254	11	0.00	28.3	21.1	972
43	12	0.03	0.08	23	16	224	12	0.05	31.1	23.3	1138	255	12	0.00	28.9	20.0	987
44	13	0.15		23	16	225	13	0.00	30.6	21.1	1149	256	13	0.00	29.4	20.0	636
45	14	0.03		24	17	226	14	T	28.9	21.1	1155	257	14	0.00	29.4	21.1	548
46	15	0.02		24	18	227	15	0.05	28.9	21.7	857	258	15	0.00	28.9	20.6	974
47	16	0.07	0.31	23	21	228	16	0.00	28.9	21.1	1247	259	16	0.02	28.3	20.0	823
48	17	0.03	0.04	23	17	229	17	0.05	29.4	21.7	1050	260	17	0.07	29.4	21.1	992
49	18	0.03	0.08	25	17	230	18	0.12	26.1	21.1	585	261	18	0.00	28.9	21.1	773
50	19	0.00	0.00	25	15	231	19	0.00	28.3	20.6	1172	262	19	0.00	29.4	22.2	986
51	20	0.00		24	15	232	20	0.02	27.8	21.1	918	263	20	0.04	27.2	21.1	522
52	21	0.00		23	15	233	21	0.07	27.2	21.1	987	264	21	0.00	28.9	20.6	1011
53	22	0.12	0.16	23	15	234	22	0.09	27.8	20.6	1216	265	22	0.01	27.8	20.6	721
54	23	0.40	0.49	23	17	235	23	0.00	28.3	20.0	1071	266	23	T	27.2	21.1	742
55	24	0.56	0.42	25	16	236	24	0.00	28.9	19.4	1163	267	24	0.00	28.9	20.6	874
56	25	0.93	1.41	25	16	237	25	0.00	28.9	20.0	906	268	25	0.10	28.3	21.1	848
57	26	0.01	0.06	21	16	238	26	0.00	27.8	20.6	650	269	26	0.01	30.0	21.7	1007
58	27	0.65		23	17	239	27	0.07	30.0	20.0	1109	270	27	0.00	30.0	19.4	1532
59	28	0.28		23	15	240	28	0.00	29.4	20.6	1393	271	28	T	31.1	21.7	326
60	29	0.05	1.06	23	16	241	29	0.05	28.9	21.1	1245	272	29	0.00	27.8	20.0	552

Climatic data in three environments during the experiment.

Kauai 87/88					
Julian		Rain (")		Temp.C	
Date	Date	Site 1	Site 2	Max	Min
61	Mar. 1	0.00	0.00	24	16
62	2	0.00	0.00	24	15
63	3	T	T	24	14
64	4	0.00	0.00	24	14
65	5	0.07		25	14
66	6	0.43		23	16
67	7	0.06	0.60	22	18
68	8	0.02	0.04	22	17
69	9	0.00	0.00	25	17
70	10	T	T	25	17
71	11	0.03	0.03	25	16
72	12	0.02		25	16
73	13	0.00		25	17
74	14	0.00	0.03	24	16
75	15	0.38	0.42	24	15
76	16	0.05	0.09	19	14
77	17	0.23	0.24	22	14
78	18	0.00	0.00	23	15
79	19	0.53		24	15
80	20	1.49		23	17
81	21	0.93	2.96	24	18
82	22	0.00	0.00	24	18
83	23	0.23	0.25	23	18
84	24	1.12	1.00	23	18
85	Harvest	0.10		25	16
	Total	46.93	51.09		

Poamoho 88					
Julian		Rain	Temp.C		Solar
Date	Date	(")	Max	Min	Rad
242	30	0.01	28.3	21.1	1119
243	31	0.02	29.4	21.1	1112
244	Sept 1	0.00	28.9	21.1	1084
245	2	0.00	28.9	20.6	1024
246	3	0.00	30.6	20.6	1343
247	4	0.00	30.6	21.7	1123
248	5	0.00	31.7	20.6	1277
249	Harvest	0.00	29.4	22.2	741
	Total	3.84			

Poamoho 89					
Julian		Rain	Temp.C		Solar
Date	Date	(")	Max	Min	Rad
273	30	0.00	28.3	20.6	525
274	Oct. 1	0.01	28.9	22.2	444
275	Harvest	0.04	27.8	21.7	595
	Total	3.79			

Solar radiation measurement were from integrator type LI-COR instrument (model LI-500, Sr.No. Int. 219-7604